THE UNIVERSITY OF QUEENSLAND

Bachelor of Engineering Thesis

Increasing the Strength and Stiffness of Structural Laminated Timber using Natural Fibre Composites

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Abstract

Structural timber with low mechanical properties and/or large defects will be downgraded to non-structural uses with a subsequent loss in value. Using a low-cost natural fibre reinforced polymer (NFRP) material with a high stiffness and strength in conjunction with laminated timber veneer products, such as laminated veneer lumber (LVL) and plywood, may allow for the use of lower quality timber in structural applications. A NFRP veneer-like sheet is proposed to be included as outer layers of LVL and plywood products.

Two minimal-processing methods were identified for the fabrication of industrial hemp stems into unidirectional-fibre composite sheets with high tensile strength and stiffness at a low cost. Comparison to reported properties in literature and the plywood stress grading system indicate strong stiffening potential of the hemp composite in structural applications.

Finite Element (FE) models were validated with 4-point flexural testing of timber laminates and used to compare the cost and performance of using hemp composite sheets as outer layers of plywood and scaffold plank laminates. This suggests that the addition of the composite is able to reduce costs for both constant bending stiffness and constant thickness laminates based on estimated costs of timber plies and the composites materials.

Small-scale timber laminates incorporating hemp composite sheets pointing towards further applications of the hemp composite including decorative panels requiring an aesthetic finish.

The successful implementation the hemp composite in timber laminates could boost the profitability of Queensland and Australia's timber industry, allowing for cheaper or downgraded timber to be used in high stiffness laminates.

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1 Introduction

1.1 Motivation

The growing, processing and retailing of timber and wood-based products is one of Queensland's oldest and most durable industries. It contributes approximately $4 billion of economic activity across its full value chain, including $1.3 billion in the wood product manufacturing sector [1]. The industry has experienced long-term structural changes over the last 20 years as it transitioned to a predominantly plantation-grown resource. Presently the industry is facing extremely difficult local market conditions and competition from imported products, particularly in the primary processing sector [2].

Some of the key challenges include: [2]

- Low profitability and return on investment across the industry.
- Substitutions of non-renewable building products replacing timber.
- Declining research and development capability.
- Poor public awareness of the environmental benefits of wood products and concerns about harvesting forests.
- Declining availability of reliable industry data.

The Forest and Timber Industry Plan Working Group was created in 2012 with the aim of identifying and implementing practical strategies to assist in realising potential growth opportunities for the Queensland forest and timber industry over a 30-year timeframe. Priorities include developing the market for timber products through strategic promotions, encouragement of the use of timber in the building industry, and reducing regulatory restriction and compliance costs imposed on timber processing and manufacturing [3]. This situation provides a number of opportunities for the introduction of timber products able to maximise profitability and expand on traditional markets. Construction is currently the predominant market in Queensland and is an obvious candidate for implementation of a suitable product [2]. Additionally, engineered wood products are representing an increasing proportion of the timber market and are frequently marketed as part of integrated timber-based building systems that have improved technical specifications and reliability relative to solid wood products [3].

1.2 Potential Products

Structural pine is graded before distribution predominantly based on its stiffness with the use of industrial scale x-ray scanners. Beams that have large, through-thickness defects including knots from branches and shake (separation of adjoining layers of wood) will be downgraded to non-structural timber, incurring a subsequent loss in value. Removing part of the affected area and inserting a 'patch' of a foreign material with a higher stiffness than the timber may be able to increase the strength and stiffness of the beam to a structural grade in a cost effective manner.

Another possible value-adding measure exists in the manufacturing of laminated timber products including Laminated Veneer Lumber (LVL) and Plywood. Due to the strict dimensional and load bearing constraints on many LVL products, a high grade of timber is required at a high cost. More expensive hardwood plies are also used in some applications. Replacing plies close to the outer surface with a higher strength and stiffness material may allow the use of lower grade timber for the remaining plies, while maintaining or increasing the strength and stiffness of the LVL in a cost effective manner.

Natural fibre composites are a potentially ideal choice as a strengthening and stiffening material due to their very good directional properties, compatibility with conventional laminate glues and their environmental benefits, especially in disposal.

1.3 Aims

A Natural Fibre Reinforced Polymer (NFRP) material has been nominated as the preferred composite material type to be developed. The aim of this thesis is to develop and suitable natural fibre composite material able to be manufactured into a veneer-like sheet to be used as layers in LVL and Plywood laminates. Its purpose is to increase the strength and stiffness of the products in a cost effective manner by allowing lower grade timber to be used for the remaining plies. This should be developed in a way that can be automated and is able to be integrated into conventional LVL and plywood manufacturing equipment with minimal modification to the processing method.

1.4 Expected Outcomes

A cost effective natural fibre composite-laminated wood product has potential to boost the profitability of Queensland and Australia's timber industry, directly affecting the product manufacturing sector by adding value to lower quality timber that may otherwise be unsuitable for structural applications. Forestry and logging industries could also be affected by increased demand for lower quality softwood timber. This relies strongly on the composite product and manufacturing process being practical on an industrial scale and having significantly improved structural properties to available wood products.
A secondary outcome is to benchmark existing LVL and Plywood products in terms of their cost and performance against products with the inclusion of natural fibre composites.

Adoption of a similar product could initiate the development of natural fibre composites for use in the engineered timber industry in products including scaffold planks, flooring and other structural applications.

2 Literary Review

The literary review aims to give an overview of state-of-the-art research surrounding natural fibre reinforced polymer (NFRP) materials, modelling techniques used to analyse structural properties of NFRP's, an overview of laminated timber veneer products, and mechanical testing procedures for composites and timber constructions. This is primarily to familiarise readers with important concepts and clarify terminology and processes used in the rest of the document.

2.1 Natural Fibres

2.1.1 Introduction

In a composite structure, fibres act as a reinforcement to enhance the mechanical properties of the binding matrix phase [4]. This thesis will consider lignocellulosic (plant based) natural fibres which are grouped into leaf, bast, seed and fruit as their origin. Bast and leaf varieties and so-called hard fibres and are most commonly used due to their generally higher performance [5].

2.1.2 Advantages and Disadvantages

Fibres derived from annually renewable resources provide environmental benefits with respect to ultimate disposability and raw material utilisation [4]. They offer advantages over traditional reinforcing materials such as glass fibres, talc and mica. These include low density, high toughness, acceptable specific strength properties, reduced tool wear, reduced dermal and respiratory irritation, good thermal properties, ease of separation, enhanced energy recover and biodegradability [4, 6]. They are also abundantly available and less expensive [6]. Energy required for production of natural fibres is on average less than half the amount needed for synthetic fibres [7].

A major constraint on the adoption of natural fibres as reinforcements in composites is the variability of the mechanical properties of these fibres [8]. Another critical drawback is their hydrophilic nature which lowers compatibility with hydrophobic polymeric resins during fabrication. Natural fibres require relatively low required processing temperature of not more than approximately 200°C due to the possibility of degradation and/or volatile emissions that could affect composite properties, although it may be acceptable to use higher temperatures for short periods [4]. Natural fibres have inherently low dimensional stability and are susceptible to shrinkage and swelling [6].

2.1.3 Plant Types

As well as mechanical properties, the ideal choice of a low-cost natural fibre will be strongly dependent on local growing conditions and availability. A brief overview of some of the most important natural fibres is given below.

Flax is most commonly in planted in Europe, although it is now grown in many agricultural environments around the world. It is used in the car industry for components including door panels, roofs and boot linings [4, 9].

Hemp originates from central Asia and is cultivated in many temperate countries [4]. It does not require fertiliser, herbicides or pesticides to grow well and hence is potentially of great interest in the context of sustainability. It is now finding use in matrix composites for internal structures in similar automotive applications to those for flax fibres [9].

Sisal is widely grown in tropical countries in Africa, West Indies, Tanzania and Brazil [4]. Its structural leaf fibres have been a leading material for agricultural twine due to its strength, durability, ability to stretch and resistance to deterioration in salt water [10].

Jute is the second most common natural fibre (after cotton) cultivated in the world, primarily grown in Bangladesh, Brazil, China, India and Indonesia. It is commonly used in matrix composites for the German automotive door-panel industry [9].

Kenaf is a crop native to grown commercially in the U.S, able to yield multiple crops per year due to its very fast growth rate. It is similar to jute in many of its properties and is often used as an alternative to, or in combination with jute [4, 9].

2.1.4 Composition of Natural Fibres

The principal components of the fibre cell walls are cellulose, hemicelluloses and lignin, with pectin considered to be the main binder [9]. Waxes and other extractives also exist in smaller amounts [11]. In all cases cellulose is the main component of natural fibres and the most important structural component [5, 9]. The amount of cellulose varies depending on the species and age of the plant. Cellulose consists of strong, crystalline chains containing hydroxyl groups, which form hydrogen bonds among cellulose macromolecules and with hydroxyl groups in the air. Because of this, natural fibres are hydrophilic with a moisture content ranging between 8% and 12.6% [4, 6].

Lignin is a biochemical polymer which functions as a structural support material, influencing the fibre structure, properties and morphology. During synthesis of plant cells, cellulose and hemicellulose are laid down first before lignin fills the space between these fibres to cement them together and stiffen the cell walls [4]. The result is helically would cellulose microfibrils in an amorphous matrix of lignin and hemicellulose [6]. This composite-like structure allows natural fibres to be competitive with synthetic fibres in terms of specific properties [7].

The waxy substances generally influence the fibre's wettability and adhesion characteristics [4] and can be eliminated by extraction with organic solvents [5].Typical value ranges of fibre components and structural parameters are summarised in Table 1.

Table 1 - Chemical composition and structural parameters of common natural fibres [5, 6]

Natural Fibre	Cellulose (wt.%)	Hemi-cellulose (wt.%)	Lignin (wt.%)	Pectins (wt.%)	Wax (wt.%)	Moisture Content (wt.%)	Cell Length (mm)	Micro-fibrillar spiral angle
Hemp	70.2-74.4	17.9-22.4	3.7-5.7	0.9	0.8	10.8	5-55	6.2°
Flax	71-78	18.6-20.6	2.2	2.2-2.3	1.7	10.0	5-60	10.0°
Jute	6171	13.6-20.4	12-13	0.2	0.5	12.6	1.5-5	8.0°
Sisal	67-78	10.0-14.2	8.0	10.0	2.0	11.0	0.8	20.0°
Kenaf	53-57	15-19	5.9-9.3	-	-	-	2.6-4	-

2.1.5 Bast Fibre Structure

Stems consist often of a hollow cylinder at the centre known as the pith, surrounded by the xylem layer, phloem, bast fibres, cortex, epidermis and cuticle. The bast and cortex part of the stem contains the longest fibres which are of most significant interest as reinforcing fibres for composites [12]. Figure 1 shows a typical stem cross-section. During cell growth, a primary cell wall is first formed in which there is a somewhat random alignment of cellulose microfibrils. A secondary wall then forms within the primary wall consisting of three layers. In these layers the cellulose microfibrils have much more precise orientations. The spiral angle and volume fraction of microfibrils in the thick middle layer of the secondary wall are considered to have the greatest influence on the fibre properties. Within the secondary cell wall is a hollow tube called the lumen [11].

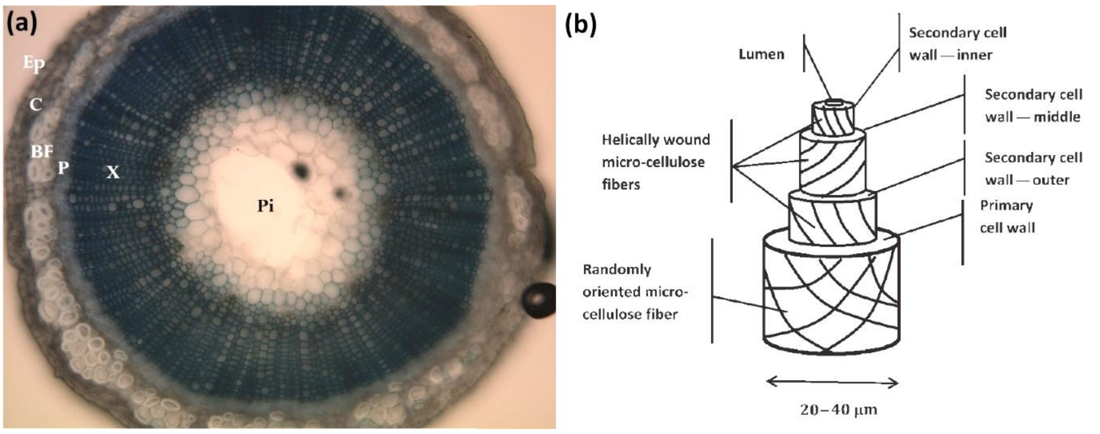


Figure 1 - Bast fibre structure. (a) Flax stem cross-section showing underlying tissues. Ep=epidermis, C=cortex, BF=bast fibres, P=phloem, X=xylem, Pi=pith [13]. (b) Typical arrangement of microcellulose fibres in the cell wall [11].

2.1.6 Fibre Quality

Conventional fibres such as glass, carbon, aramid, etc., can be produced with a definite range of properties, while properties of natural fibres vary considerably. This depends on which part of the plant the fibres are taken from, the cultivating practices and growing region, the age of the plant, and the preconditioning [4], especially after retting. Potentially harsh conditions during harvest may also introduce damage and it is common to observe mechanical damage to extracted fibres [9].

Natural fibres do not exhibit constant dimensional characteristics of many commonly used synthetic fibres which are assumed to have regular circular cross-sections. Natural fibres are not circular and the dimensions and chemical composition of each cell in the fibre will change along the length. The hollow lumen introduces additional porosity into the composite and reduces the cross- section of fibre material available to carry load. Voids in synthetic fibres are comparatively rare [9].

2.1.7 Mechanical Properties

Desirable properties for fibres include a high modulus, high tensile strength, high durability, low density, good moldability and recyclability [6]. Mechanical properties are related to the internal structure and chemical composition of fibres. The fibrils of cellulose form spirals along the fibre axis. The strength and stiffness of the fibres correlates with the angle between the cellulose molecules and the fibre principal axis for bast fibres [5, 9]. While it is not possible to directly correlate properties with cellulose content and microfibrillar angle due to the very complex structure of natural fibres, generally a high cellulose content and low microfibrillar angle are attributed to higher mechanical properties [4]. As cellulose is a hydrophilic molecule, the fibre properties are dependent on the water content. As water penetrates the amorphous regions of cellulose, the stiffness can drop by a factor of 2 to 4, as the stiffening contribution of the hydrogen bonds is progressively removed [9].

The chemical structure of cellulose from different natural fibres is identical, however the degree of polymerisation (DP) varies. Bast fibres commonly have the highest DP among plant species causing them to have generally superior stiffness and strength [4]. Cellulose has been estimated to have a modulus of 140GPa which is comparable with that of synthetic aramid fibres, however experimentally measured moduli will be lower due to less than 100% crystallinity and off-axis fibre orientation [9]. A summary of mechanical properties of common natural fibres is given in Table 2.

Table 2 - Properties of common natural fibres [4, 5, 9, 14-17].

Natural Fibre	Density (g/cm^3)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Elongation (%)	Cost (AUD/kg)
Hemp	1.47-1.48	20-73.5	310-920	1.6-1.7	1.11-2.22
Flax	1.40-1.50	24-100	300-1400	1.2-3.3	2.22-4.44
Jute	1.45-1.46	10-55	200-860	1.5-2.0	0.38-1.61
Sisal	1.33-1.45	9-38	100-700	2.0-3.0	0.64-0.75
Kenaf	1.19-1.45	3-53	300-930	1.6-2.9	0.28-0.56

2.1.8 Processing Techniques

Fibres can be modified by physical and chemical methods. Some common processing techniques are outlined below.

Retting is the subjection of the crop to chemical or biological fermentation treatments to make the fibre bundles more easily separable from the woody part of the stem. Termination of the retting process may be problematic and failure to achieve this can result in reduced fibre properties [9].

Decortication is the mechanical removal of non-fibrous material from retted stalks, or from ribbons or strips of stem to extract the bast fibres. This is usually achieved by a manual operation, hammer mill, inclined planted/fluted rollers, or willower. The proportion of fibre extracted from a stem may be less than 10% by weight [9].

Dessication or drying of the crop has numerous advantages over field retting including earlier harvesting, elimination of the need for swathing (drying after being cut), reduction in combining time and less wear on machinery [9].

Carding is a process to disentangle and align fibres by working them between two closely spaced, relatively moving surfaces clothed with pointed wires, pins, spikes or saw teeth.

Acetylation is used to describe the process of combining cellulose with acetic acid. The reduced number of hydroxyl groups after acetylation confers a more hydrophobic character to the fibres.

Scouring (solvent treatment) is the treatment of textile materials in aqueous or other solvents in order to remove natural fats, waxes, proteins and other constituents, as well as dirt, oil and other impurities [9].

2.1.9 Natural Fibre Fabrics

Fibres are commonly processed into a yarn through spinning, which is the drafting and twisting of the fibres [9]. The main advantage of spun yarn is the ability to weave then into 2D and 3D fabrics with tailored orientations. Yarn from natural fibres also present some short fibres protruding from the main yarn body which can lead to better mechanical interlocking with composite resins. This however, requires a significant amount of processing and can be labour intensive [7].

2.2 Resins for Natural Fibre Composites

2.2.1 Introduction

The topic of composite resins, including chemical structures, curing cycles and additives, is a broad and very complex topic. Therefore, only a brief overview will be presented. The Department of Agriculture and Fisheries Salisbury Research Facility has extensive experience with adhesives for timber and natural fibre products and will assist with selecting a preferred polymer matrix material.

Natural fibre composite structures typically use a petrochemical based resin as the matrix phase. Its function is to secure the fibres together, transfer mechanical loads to the fibres and act as a barrier to protect the fibre surface from mechanical or environmental damage. The polymer material generally has a low modulus which is increased with the addition of high modulus fibres as a functional filler [17].

The choice of polymer matrix is limited by the thermal decomposition temperature of cellulose fibres at around 200°C. This is a time dependent response and degradation process will begin at approximately 180°C depending on the fibre type, resulting in a decrease in mechanical properties [9].

2.2.2 Thermoset Resins

Thermoset resins crosslink during curing by either an addition of curing agents or by heating. As a result of crosslinking, thermoset plastics generally have better strength and stiffness than thermoplastics, making them attractive as matrix resins in fibre-reinforced plastic composites [18].

Common thermoset resins used as matrices include phenolic resins, epoxy, unsaturated polyester, vinyl ester and polyurethane. The degree of hydrophilicity of these matrices allows for acceptable interfacial bonding with the lignocellulosic fibres, even before surface modification, through the formation of covalent bonds. Furthermore, most thermoset resins can be processes and cured at moderate temperatures, normally below the degradation point of lignocellulosic material [10]. A brief overview of some common thermoset resins is provided below.

Unsaturated polyester resins are widely used in commercial, mass-production applications due to their ease of handling, good balance of mechanical, electrical and chemical properties, and relatively low cost. They are typically coupled with glass fibre reinforcements. Catalysts and accelerators are added to the resin prior to moulding to activate crosslinking otherwise the rate of polymerisation is too slow to make composite moulding practical [19].

Vinyl ester resins offer a bridge between low-cost, rapid-curing and easily processed polyesters and higher-performance epoxy resins. Their molecular structure is very similar to that of polyester, but with reactive sites only at the ends of molecular chains and with fewer ester groups. Since ester groups are susceptible to hydrolysis, less of these increases vinyl esters' resistance to water and chemically corrosive environments [19].

Epoxy resins contribute higher strength and durability than polyester and vinyl ester resins. They typically cure by reaction with amines or anhydrides. A hardener, also known as a curing agent, is used to cure the resin which reacts with the base resin in an addition reaction. It is critical to use the correct mix ratio in order to ensure a complete reaction, allowing the resin to fully cure and attain its maximum mechanical properties [19]. Ampreg 22 is an epoxy resin produced by Gurit. Fast, standard, slow and extra slow hardeners are available to be used with the base resin. The curing time decreases with increasing temperature, down to a curing time of approximately one hour when using the fast hardener [20].

Thermosetting polyurethane products are state-of-the-art composite resins and a popular replacement for polyester and vinyl ester. Polyurethanes are less brittle and have better impact and fatigue resistance, as well as similar tensile and flexural strengths. They generally have lower stiffness, however this is not of primary importance when using a high volume fraction of reinforcing fibres. Polyurethane also offers environmental advantages over polyesters and vinyl esters being BPA free, styrene free, and producing very low emissions during processing [21].

2.2.3 Compatibility with Natural Fibres

The adhesion between fibre and matrix is obtained by the mechanical anchoring of the fibre ends into the matrix. Polymers in which the chemical bonding with reinforcements made of cellulose are known as methylolfunctional polymers. Methylol groups react with the hydroxyl groups of the cellulose to form stable ether linkages and a high compatibility is achieved. Phenol-formaldehyde is the only example of a high compatible cellulose-polymer compound [5]. In other cases, the absorption of moisture by untreated fibres, poor wettability and insufficient adhesion between polymer matrix and fibre leads to de-bonding over time [5]. Compatibility between fibres and matrices has been found to be achieved using polymers that favour entanglement and interdiffusion with the matrix [22].

The wettability of the fibre depends on the viscosity of the polymer and the surface tension of both materials. The surface tension of the polymer must be as low as possible and at least lower than that of the fibre [5]. Without effective wetting of the fibre, strong interfacial adhesion cannot exist. The lack of interfacial interactions leads to internal strains, porosity and environmental degradation [5].

2.2.4 Mechanical Properties

Most composite properties are dependent upon the combination of the matrix and reinforcement together. However, some properties will be determined largely by the reinforcement property with little contribution from the matrix, while in other, the matrix will dominate. These properties are generally the thermal properties, flammability and environmental resistance, though the shear modulus may be important mechanically, depending on the anticipated loading [23]. A summary of important mechanical properties of common thermosetting polymer matrices is given in Table 3.

Table 3 - Mechanical properties of common non-reinforced matrix materials [15, 16, 20, 23, 24].

Matrix material	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Tensile Strength (MPa)	Elongation (%)	Moisture absorption (%)	Cost (AUD/kg)
Polyester	1.2-1.5	3.6 – 4.3	0.7 – 1.6	55 - 65	1.4 – 4.0	0.15 – 0.6	4.1 – 4.6
Epoxy	1.1 – 1.4	3.4 – 3.9	0.8 – 1.0	50 - 85	2.3 – 4.5	1.1 – 2.3	2.3 – 2.6
Vinyl Ester	1.2 – 1.4	3.0 – 3.7	1.2 – 1.4	72 – 80	5 - 8	0.2 – 0.9	4.8 – 5.3
Polyurethane	1.0 – 1.1	4.1 – 4.3	1.4 – 1.6	69 – 76	3 - 6	0.1 – 0.2	4.4 – 4.9

2.3 Natural Fibre Reinforced Polymer (NFRP) Composite Structures

2.3.1 Introduction

The advantage of fibre-reinforced composites results from the controlled structure in which the fibres lie in the matrix. Natural fibre composites will generally have lower strength and stiffness than conventional composites, however they are able reduce the total mass due to their lower density. They also offer economical production with low requirements on equipment and can be more readily recycled [5].

A major constraint on the effective use of natural fibre reinforcements is that the materials supply chain does not have a cost-effective, environmentally friendly methodology for the production of woven or otherwise aligned fabrics. Additionally plants grown in temperate regions are normally harvested only in late summer or autumn which has significant implication for the supply chain [9].

For an isotropic matrix, the use of a single stiffness parameter E_m is an accepted approximation. In contrast, anisotropic fibres have five independent parameters or elastic constants (E_1, E_2, G_{12}, ν_{12}, ν_{23}) that are required to fully determine the elastic properties [25]. This is experimentally complicated and typically involves fitting of analytical and semi-empirical models to determine the values of the non-measurable parameters [26]. Expected ranges of values of the elastic constants are given as: E_1 = 20-80GPa, E_2 = 5-9GPa, G_{12} = 3-8GPa, ν_{12} = 0.1-0.3. In stiffness calculations for this analysis, a single fibre stiffness parameter E_f will be applied corresponding to E_1, and is the parameter referenced in Table 2. This is valid only for a unidirectional fibre orientation [25].

2.3.2 Effect of fibre volume fraction and porosity

For relatively high fibre volume fractions the modulus of the composite material will increase with fibre content [17]. Increasing alignment of the fibres enables more fibres to be incorporated into the composite due to the voids created, depending on the orientation of the fibres in the matrix.

For practical purposes, the limiting fibre volume fractions are around 75% for unidirectional fibres, 65% for woven fibres and 30% for randomly oriented fibres [9].

The elastic modulus E_c of a composite material can normally be predicted using the standard rule-of-mixtures shown in Equation (1) for axial loading. V_f and V_m are the volume fraction of the fibre and matrix phases, and E_f and E_m are the individual moduli of the fibre and matrix phases [27].

$$E_c = V_f E_f + V_m E_m \tag{1}$$

This is the theoretical maximum composite modulus assuming the fibres are uniformly distributed throughout the matrix, there is perfect bonding between fibres and matrix, the matrix is free of voids, applied loads are parallel to the fibre direction, there are no residual stress, and the fibre and matrix phases behave as linearly elastic materials [28]. This however neglects porosity in the composite making Equation (1) inappropriate for calculating the stiffness of natural fibre composites. Fibre-correlated porosity is air-filled cavities inside the fibres (lumen) which can be significant and air-filled cavities at the fibre/matrix interface. Matrix-correlated porosity is largely due to entrapped air bubbles. Porosity has been demonstrated to be well simulated by including the factor $(1 - V_p)^n$ in the rule of mixtures model shown in Equation (2) [25, 29].

$$E_c = (V_f E_f + V_m E_m)(1 - V_p)^n \tag{2}$$

The porosity efficiency exponent is denoted by n, quantifying the effect of porosity giving stress concentrations in the composite. It should be noted that Equations (1) and (2) neglect the very small effect of Poisson's ratio [25]. It has been found that $n = 2$ generally gives a good fit to experimental data for a broad range of plant fibre composite systems. The porosity volume fraction V_p can be determined using optical or electron microscopical techniques with image analysis [27]. Madsen et al. determined a typical value for V_p of approximately 0.03 for hemp yarn in PET matrix for fibre volume fractions less than 0.5 [29]. Further modifications to the rule of mixtures have been proposed to incorporate a fibre diameter distribution factor [27]. However, obtaining this requires a comprehensive study of the particular fibre and is beyond the scope of approximate calculations for this thesis.

More complex estimations of effective values of V_f, V_m and V_p have been developed to incorporate the effects of volumetric interaction where two regions of composite volumetric interaction are assumed. This will not be considered in predicted composite stiffness calculations, however it does provide a useful insight into the use of sensible fibre volume fractions. The fibre weight fraction W_f is used as the independent variable between the two regions A and B. In region A, where W_f is below the transition value $W_{f,trans}$, the volume fractions of fibres, matrix and porosity respectively are governed by the densities of fibres and matrix. The porosity phase in region A is termed *processing related porosity*. In region B, W_f is above $W_{f,trans}$. The fibre assembly is compacted to its minimum volume under the operating processing conditions, which means that the volumetric interaction is constrained to a maximum obtainable fibre volume fraction $V_{f\,max}$. $V_{f\,max}$ was previously cited in Section 2.3.2 as approximately 75% for unidirectional fibres. In region B an additional porosity phase called *structural porosity* is produced due to the situation where the available matrix volume is insufficient to fill the free space in the fully compacted fibre assembly [25]. As can be seen in Figure 2, the transition between regions A and B where W_f is equal to $W_{f,trans}$ is the best possible combination of high fibre volume fraction and low porosity which leads to maximum obtainable material properties.

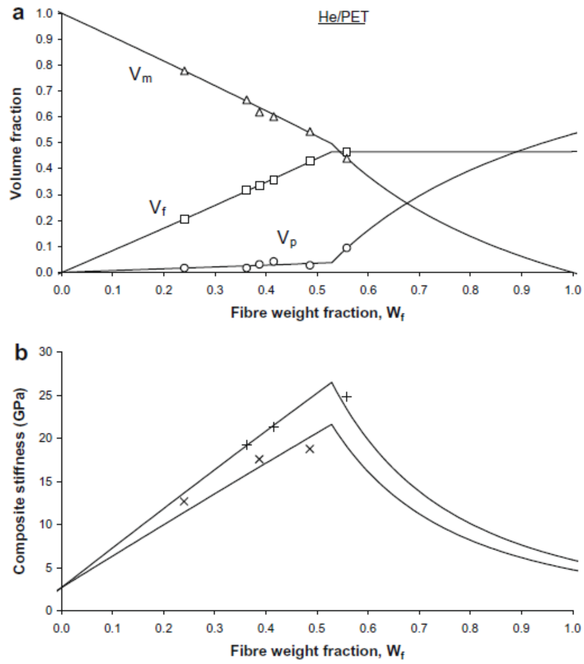


Figure 2 - Hemp/PET composites. (a) volumetric composition. (b) stiffness as a function of the fibre weight fraction. Lines are model simulations of the experimental data [25].

Madsen et al. shows that for a Hemp yarn-PET composite the practical upper limit of V_f to be approximately 0.5. Increasing V_f above this value caused the quality of the fabricated laminate to be severely deteriorated as the fibres were poorly impregnated by the matrix. Consequently, the practical maximum attainable values of axial stiffness and ultimate strength of the composites were just over 28GPa and 280MPa respectively [29].

2.3.3 Interfacial Compatibility

The properties of the composite depend on those of the individual components and their interfacial compatibility. For realisation of the full mechanical performance of the reinforcement it is critical that there is effective load transfer by shear between the fibre and matrix. This is a function of the chemical and physical bonds between them [5, 9]. Interfacial behaviour is problematic because natural fibres are generally more hydrophilic than matrix polymers, hindering wetting of fibres, and because the surface of natural fibres are physically and chemically non-uniform. This can result in regions of poor interfacial shear strength along the fibres [30]. Alterations are often required to modify the hydrophilic nature of the fibres and produce a functioning interface [27]. The main approaches to enhancement of the interaction between fibres and matrix are surface modifications of the fibre (chemical or physical), application of coupling agents to the fibre surface and/or the use of compatibilisers in the matrix [9, 27].

2.3.3.1 Fibre Surface Modifications

Lignin in the bast fibres is more hydrophobic than hemicellulose which has the potential to alter the wettability of the fibre by different resins [11]. Lignin is more hydrophobic than cellulose and thus may allow better surface interaction with hydrophobic polymer matrices. This is counter to surface modifications targeted at reacting surface hydroxyl groups as there will be fewer hydroxyls available on a lignin surface than one that is predominantly cellulose. Caustic treatments are often applied to natural fibres as a way of reducing lignin and increasing hydroxyl groups on the surface. Truss et al investigated the effects of different treatments on the surface characteristics of hemp natural fibres in the form of a non-woven mat, primarily using XPS and SEM analysis techniques. This concluded that as-received and water washed sample surfaces were devoid of cellulose but lignin rich with some extractives. Caustic treatment with NaOH still produced less than 10% cellulose at the fibre surface. Also of interest, the study indicated that the surfaces of the fibres remained non-uniform after washing and with NaOH treatment [30].

This research indicates that surface modifications aimed at removing lignin and producing a cellulose rich fibre surface may be an ineffective approach, especially for hemp fibres. There is also no indication that a lignin rich fibre surface is undesirable. The most significant and important problem appears to be the non-uniformity of the fibre surface, which may lead to areas of good and poor interfacial bonding along the fibre length. This weakens the overall composite since the areas of poor bonding are potential initiation sites for microcracks.

Silane treatment is commonly used as a coupling agent with glass fibres. It is thought that silanes are able to react with the hydroxyl groups on the fibre surface, however the effect of silane treatments on the mechanical properties of natural fibre-polymer composites has been varied and inconsistent [11].

2.3.4 Influence of Fibre Length

For discontinuous fibres, the applied load is transferred to the fibres by means of shear forces at the fibre-matrix interface. As the matrix has a much lower modulus than the fibre it will strain more upon loading. This occurs at a distance from the fibre. At the boundary between the fibre and matrix, the strain is limited by the fibre. For a composite under tension, the shear stress will be transferred to the fibre over its full surface area in contact with the matrix. The importance of the interface between fibre and matrix becomes apparent when considering this mechanism. This makes the force on the fibre a minimum at its ends and maximum at the centre region. To achieve effective strengthening and stiffening, the fibres must be larger than a critical length L_c. This is the minimum length at which the centre of the fibre will reach ultimate tensile strength simultaneously as the matrix reaches maximum shear strength [31].

A fibre of sub-critical length cannot be fully stressed and will be pulled out of the matrix, while a supercritical fibre length can be stressed over a much greater proportion of the fibre. Once the stress in the fibre reaches the fibre's tensile strength, fibre facture will occur. L_c is defined as

$$L_c = \frac{d\ \sigma_{fu}}{2\tau_m} \quad (3)$$

where τ_m is the shear stress on the fibre-matrix interface, d is the fibre diameter, and σ_{fu} is the ultimate fibre strength [17].

2.3.5 Toughness of Composites

While both fibre and matrix constituents individually behave in a brittle manner, the composite structure may be able to sustain high stresses under repeated loading, indicating the material has a high toughness. Toughness is an important property for composites, especially when used in a harsh service environment. Composites have high toughness due to the composite structure providing additional energy absorbing mechanisms when undergoing fracture. As well as matrix deformation and fibre fracture, the energy associated with debonding of the fibre-matrix interface and crack deflection, and fibre pull-out increase the fracture toughness. Fibre pull-out is the most prominent energy absorbing mechanism which raises the toughness of fibre composites when fibres are pulled out of their sockets in the matrix during crack advance. This is able to take place after interfacial debonding and fibre fracture away from the crack plane have occurred beforehand [32]. For brittle matrices, a weak interface is desirable for high toughness as this allows interfacial debonding, crack deflection, fibre fracture, and fibre pull-out to occur. However a strong interface is always necessary for high stiffness [17, 32].

2.3.6 Continuous Fibre-Reinforced Thermoset Composite Processing Techniques

The simplest composite fabrication technique is the hand lay-up method. Fibres in the form of a mat or fabric are placed in an open mould and wetted with liquid resin. Curing can be carried out at room temperature or at elevated temperature to increase the curing rate. Additional post-curing at elevated temperature can also be performed. This process is generally used for low performance components as accurate fibre volume fractions and a good surface finish may not be difficult. Generally this process will produce composites with a low volume fraction and high levels of porosity. For higher performance composites, vacuum bagging the of wet-layup or pre-impregnated (prepreg) materials are used. An autoclave is used for very high performance materials, adding external pressure to the bag [18].

Resin infusion is a process where resin is infused into a mat or fabric preform under the application of pressure and/or a vacuum. This can be performed through resin transfer moulding (RTM), using a two-piece closed mould into which the fibre preform is placed and the resin is then infused. Alternately this can be performed through vacuum bag resin infusion where a plastic film is placed over the preform and sealed to form a vacuum bag. On applying a vacuum, the resin is drawn into the mould cavity, thereby infusing the preform. These closed mould processes generally produce more consistent parts than open mould processes, as well as avoiding emissions from the resin into the atmosphere [18].

High performance composites can also be manufactured using compression moulding techniques. In this process the mould cavity is loaded with the reinforcement fibres and liquid resin is added before heated male and female platens are closed to allow curing under high pressure. This requires expensive steel tooling and an automated resin distribution system [18].

2.3.7 Typical Mechanical Properties

Reported properties of various unidirectional (UD) NFRP composites are listed in Table 4. The tabled values are for the composite with the highest elastic modulus in each paper.

Table 4 - Reported mechanical properties of unidirectional NFRP composites

UD Fibre	Matrix	Fibre volume fraction V_f	Tensile Modulus (GPa)	Tensile Strength (MPa)	Reference
Flax	Epoxy	0.40	28	133	[33]
Flax	Vinyl Ester	0.37	24	248	[34]
Hemp	PET	0.50	27.6	277	[29]
Jute	Epoxy	36.5	6.75	62.49	[35]
Jute	Epoxy	0.5	3.184	148.3	[36]

2.4 Modelling of Natural Fibre Composites

2.4.1 Classical Laminated Plate Theory

Classical Laminate Theory is an extension of the theory for bending for homogeneous plates, but with an allowance for in-plane transactions in addition to bending moments, and for the varying stiffness of each ply in the analysis [37]. A comprehensive description of assumptions and calculation steps will not be specified, however some important consequences of laminate stacking will be clarified.

2.4.1.1 Elastic Couplings

Optimisation of laminate design seek that the laminate stresses in the presence of a given loads to be minimised. Coupling effects that occur in laminates must be considered which are reflected in the various components of the *ABD* matrix and its inverse. These are referred to as elastic couplings since the *ABD* matrix is a stiffness matrix. A visualisation of these couplings is shown in Figure 3.

D_{16} and D_{26} are responsible for the coupling of moments and deformations not normally associated with each other. For non-zero D_{16} and D_{26}, a simple bending moment results in a distorted reference surface shape, requiring an additional twisting moment to be applied to produce a simple curvature [38]. This emphasises the advantage of lamina oriented at 0° or 90° where D_{16} and D_{26} are zero and no unexpected deformations occur [38].

The presence of non-zero A_{16} and A_{26} are responsible for simple tensile loads producing a shearing strain behaviour within the laminate. This highlights the advantage of balanced laminates where identical plies are present on either side of the midplane with opposite orientation angles. In this case A_{16} and A_{26} with be zero [38].

The coupling effects of B_{ij} are numerous and very complex. Every component can be thought of as coupling a moment resultant to and extensional strain, or coupling a force resultant to a curvature.

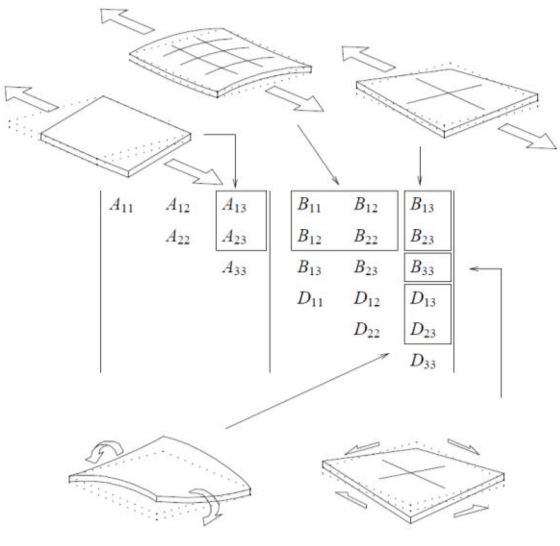


Figure 3 - Visualisation of elastic couplings on laminates [39].

2.4.1.2 Symmetric Laminates

Symmetry of geometric and material properties about the midplane, ply orientation, and ply stacking sequences all govern the form of the laminate stiffness matrices. In the case of symmetry, B_{ij} is zero and there will therefore be no bending-stretching coupling in such laminates. In-plane loads will not generate bending and twisting curvatures that cause out of plane warping, and bending or twisting moments will not produce and extension of the middle surface. This is particularly important in structures subject to changes in environmental conditions where the resulting hygrothermal forces would lead to undesirable warping in non-symmetric laminates [40]. For this reason, balanced symmetric stacking sequences are preferred [32].

The full six-by-six set of equation decouples into two three-by-three sets where the reference strains are only related to the applied axial forces only and the curvatures are related to the applied bending moments only [38].

2.4.2 Finite Element (FE) Modelling

For complex modelling of the performance of timber veneer layups and composite materials, FE modelling is an important tool, especially for optimisation. ANSYS is a developer of a range of simulation software including simulation of structures and some useful programs are discussed below.

ANSYS Mechanical APDL is an FEA software package that uses ANSYS Parametric Design Language (APDL) to create and solve simulations of mechanical parts. This is useful for analysing simple structures and materials.

ANSYS Composite PrePost (ACP) is a dedicated structural modelling tool for composite materials. This is required as composite materials are inherently difficult to simulate due to their complex structure. ACP allows creation of complex composite layups and state of the art evaluation of stresses in layers, failure criteria and complex failure mechanisms [41].

2.5 Failure Theories for Fibre Reinforced Materials

For fibre reinforced composites there are nine fundamental failure stresses to be concerned with; thee tensile, three, compressive and three shear stress. To generate failure criteria that can be verified experimentally this can be reduced to five predominant failure modes for a body under the application of an arbitrary stress state. These are axial tensile or compressive failure, transverse tensile or compressive failure, and shear failure [32]. For unidirectional fibres aligned in the direction of the applied stress, tensile failure will be governed by the tensile strength of the fibres, while tensile failure perpendicular to the fibres is controlled by the strength of the bond between the fibre and matrix, and by the strength of the matrix itself. There are many issues surrounding failure of composite materials. The polymer matrix may be ductile and exhibit substantial yielding under stress which weakens support of the fibre or degrades the load transfer mechanism. The matrix may also be brittle and exhibit significant cracking around and between fibres. This cracking will strongly influence the manner and efficiency with which load is transferred to the fibres and strongly influence the performance of the material. In contrast, failure may be due the fibres breaking or debonding and separating from the matrix. Subject to a compressive load in the fibre direction, the fibres may buckle and deform excessively which is an important consideration for bending loads where the composite will experience both tension and compression [38].

2.5.1 Maximum Stress Criterion

The maximum stress criterion is a failure criteria proposed for separate plies subject to in-plane stress states. It assumes there is no interaction between failure modes and failure will occur when the critical value for one of the failure modes is reached. These are σ_1, σ_2 and τ_{12}, corresponding to stresses in the laminar principal axes [32].

2.5.2 Maximum Strain Criterion

According to the maximum strain theory, failure occurs when at least one of the strain components along the principal material axes exceeds the corresponding ultimate strain in that direction. These principal strains are denoted ε_1, ε_2 and γ_{12}. Generally the strain criteria is expressed in terms of stress components as given below.

$$
\begin{gathered}
\varepsilon_1 = \frac{1}{E_1}(\sigma_1 - \nu_{12}\sigma_2) \\
\varepsilon_2 = \frac{1}{E_2}(\sigma_2 - \nu_{21}\sigma_1) \\
\gamma_{12} = \frac{\tau_{12}}{G_{12}}
\end{gathered}
\tag{4}
$$

Similar to the maximum stress criteria, the maximum strain criteria also assumes no interaction between failure modes, however the strain criteria will have some interaction with longitudinal and lateral stresses due to Poisson effects [42].

2.5.3 Tsai-Wu Criterion

The Maximum Stress Criterion disregards any possible effects of other stresses to the prevailing failure mode. Accounting for the presence of other stresses may result in the prediction of a different failure load. The Tsai-Wu Criterion considered more than one stress component at a time when predicting failure. The condition of no failure is given by the inequality

$$\begin{gathered} F_1\sigma_1 + F_2\sigma_2 + F_6\tau_{12} + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 \\ +2F_{12}\sigma_1\sigma_2 + 2F_{16}\sigma_1\tau_{12} + 2F_{26}\sigma_2\tau_{12} < 1 \end{gathered} \tag{5}$$

The interaction between stresses is produced through the constants F_{12}, F_{16} and F_{26}. The magnitude if the constants F_1,...,F_{66}, can be evaluated in terms of the material's ultimate principal strength terms. A reduced Tsai-Wu criterion can be produced using relations which will yield the same result as the von Mises criterion. The Tsai-Wu criterion then predicts failure when

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 - \sqrt{F_{11}F_{22}}\sigma_1\sigma_2 = 1 \tag{6}$$

where

$$\begin{gathered} F_1 = \left(\frac{1}{\sigma_1^T} + \frac{1}{\sigma_1^C}\right) \qquad F_{11} = -\frac{1}{\sigma_1^T\sigma_1^{TC}} \\ F_2 = \left(\frac{1}{\sigma_2^T} + \frac{1}{\sigma_2^C}\right) \qquad F_{22} = -\frac{1}{\sigma_2^T\sigma_2^{TC}} \\ F_{66} = \left(\frac{1}{\tau_{12}^F}\right)^2 \end{gathered} \tag{7}$$

σ^T, σ^C and τ^F refer to the ultimate failure stresses in tension, compression and shear respectively [38].

2.6 Laminated Veneer Lumber (LVL)

2.6.1 Introduction

LVL is an engineered, timber veneer product made by bonding thin timber veneers together under heat and pressure. The veneers are laid up with the grain direction of all veneers parallel to the longest dimension. In some cases, cross-banded veneers are used to improve dimensional stability and/or increase resistance to splitting when nailed. Where cross-bands are included, the veneers immediately below the face veneers are typically cross-banded. Australian Standard AS 4357 governs the requirements for manufacturing, mechanical property characterisation and verification of properties for LVL intended for structural applications. Any hardwood or softwood timber species are permitted for structural LVL. The prominent species used are radiata or maritime plantation pine [43]. Common applications LVL include scaffold planks and structural beams.

2.6.2 Grading

The stress grading of LVL is specified by the manufacturer for particular products. AS4357 requires the manufacturer to publish the design properties for their LVL or adopt a stress grade classification as given for structural timber in AS 1720.1. Alternatively, the manufacturer may determine the properties pertaining to a specific application such as scaffold planks. Veneer quality is specified by the manufacturer to ensure minimum structural properties are maintained and aesthetics are not usually a consideration [43].

For LVL planks undergoing simple bending, the modulus of elasticity, bending strength, shear strength, and bearing strength are required to be determined [44]. The shear modulus may also be determined and is taken as one-twentieth of the modulus of elasticity, except where otherwise determined by testing [45].

2.6.3 Processing Techniques

Logs are first conditioned by immersion in a heated water bath or by steam treating. This facilitates the peeling process to achieve a smooth, even veneer. After conditioning the logs are debarked and cut into suitable lengths ready for peeling. Peeling is done in a rotary lathe to produce a continuous ribbon of veneer of uniform thickness. Typical veneer thicknesses range from 1mm to 3.2mm. The continuous veneer ribbon is clipped to size and dried or continuously dried and then clipped. Drying ensures the veneer moisture content is uniform and at an appropriate value for bonding; commonly 6-12% depending on adhesive used, ambient conditions and timber species. The veneers are then sorted for veneer quality based on the manufacturer's predetermined specifications [43].

As specified by AS 4357, bonding between plies shall be Type A bonding which requires a phenolic type adhesive to be used. The bond between plies must also be continuous over the whole area other than where permitted imperfections occur [44]. LVL with Type A bonding has a glueline that will not deteriorate under the action of water or extremes of heat and cold, and will withstand long term stress without degrading [43].

Adhesive is spread onto the veneers by passing them through the rollers of a glue spreader or through a curtain coater. The veneers are then laid up and first cold pressed to facilitate the bonding process and ensure good adhesive transfer from the spread to the unspread veneers. After cold pressing the LVL is hot pressed between heated platens at a set temperature and time to achieve proper bonding. Structural LVL can also be fabricated in a dedicated LVL hot press. In this case the veneers are laid up on a conveyor belt and progressively hot pressed such that very long lengths are achieved. After pressing, LVL slabs are trimmed and sanded if required, before being individually branded to identify the product type and structural properties [43].

2.7 Structural Plywood

2.7.1 Introduction

Structural plywood is an engineered timber veneer product similar to LVL. Instead of unidirectional plies, the veneers are laid up with alternating cross-bands at 90°. The layup generally has face veneers oriented in the long direction with a symmetric, balanced construction. Australian Standard AS 2269 governs the requirements for manufacturing, mechanical property characterisation and verification of properties for plywood intended for structural applications. The majority of structural plywood is manufactured from plantation sourced radiata, hoop or slash pine [43]

2.7.2 Grading

Structural plywood is graded according to surface quality and stress grade. There are five veneer surface quality grades permitted, depending on the intended application. These are A, S, B, C and D qualities, listed in descending order of appearance. The stress grades define the plywood strength and stiffness properties. There are ten possible stress grades known as F-grades, which are detailed in Table 5, taken from AS 2269 [46]. The most common stress grades are F8, F11 and F14 [43].

Table 5 - Structural plywood: characteristic properties for F-grades. The values for short duration average modulus of rigidity are derived values using the equation G=E/20 [46].

Stress grade	Characteristic strength, MPa				Short duration average modulus of elasticity, MPa	Short duration average modulus of rigidity, MPa
	Bending (f'_b)	Tension (f'_t)	Panel shear (f'_s)	Compression in the plane of the sheet (f'_c)	(E)	(G)
F34	90	54	6.0	68	21 500	1 075
F27	70	45	6.0	55	18 500	925
F22	60	36	5.5	45	16 000	800
F17	45	27	5.1	36	14 000	700
F14	36	22	4.8	27	12 000	625
F11	31	18	4.5	22	10 500	525
F8	25	15	4.2	20	9 100	455
F7	20	12	3.9	15	7 900	395
F5	14	9.6	3.7	12	6 900	345
F4	12	7.7	3.4	9.6	6 100	305

2.7.3 Processing Techniques

Plywood uses the same conditioning and peeling processes as LVL veneers. The clipped and dried veneer sheets are then sorted into veneer surface quality grades. Bonding between veneers is also Type A bonding, analogous to LVL. Adhesive is applied only to the cross-band veneers and the veneers are laid up and pressed in a similar process as LVL, involving both cold and hot pressing. Typically layups consist of only an odd number of plies. After pressing the plywood panels are cooled and then trimmed to precise dimensions. The panels are then sanded if required and inspected for face quality [43].

2.7.4 Plywood Flooring

As for all plywood applications, a suitable F-grade and thickness of plywood can be selected based its expected loading scenario. Therefore, a thicker plywood laminate of a lower stress grade is able to be used for the same application as a thinner laminate of a higher stress grade. Table 6 shows the required concentrated and distributed loading requirements for different flooring applications. As plywood has excellent load re-distribution capabilities, the concentrated loads will almost always be limiting [43]. AS1170.0 recommends the maximum deflection of the panel to be less than span/300.

Table 6 - Summary of imposed live loads for flooring applications [47]

Flooring application	Uniformly distributed load (kPa)	Concentrated load (kN)
Residential	1.5	1.8
Assembly Areas	3.0-3.5	2.7-3.6
Offices	3.0	2.7
Retail Sales Areas	4.0	3.6
Office Storage Space, File Rooms	5.0	4.5
Public Corridors & Spaces	4.0-5.0	4.5
Stages	7.5	4.5
General Storage	2.4/m of storage height	7.0
Drill Rooms & Halls	5.0	9.0

Plywood flooring is to be laid and fixed to floor joists as shown in Figure 4. Standard joist spacing is at 400mm intervals and typical plywood dimensions are 2400x1200mm.

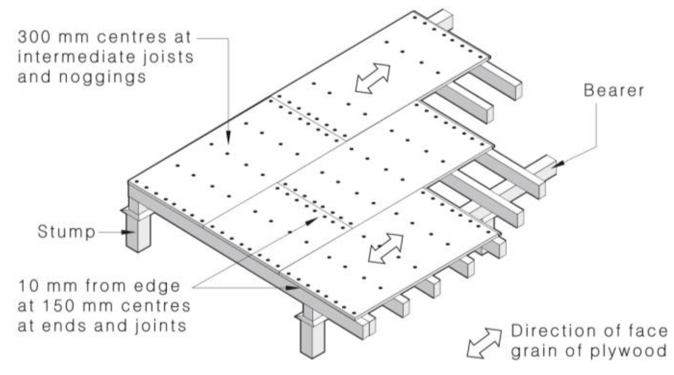


Figure 4 - Fixing of plywood sheet flooring [48]

2.8 Mechanical Testing

2.8.1 Bending Tests

A flexure test produces tensile stress on the convex side of the specimen and compression stress on the concave side. This creates an area of shear stress along the midline. To ensure the primary failure originates from tensile or compression stress, the shear stress is minimised by controlling the span to thickness ratio (L/t). Shear deformations can significantly reduce the apparent modulus of highly orthotropic laminates when they are tested at low L/t ratios. For this reason, a high L/t ratio is recommended for flexural modulus determinations [49]. The flexural modulus of elasticity is determined by load-deflection measurements at stresses below the proportional limit [50].

Three-point flexure testing is the simplest bending test consisting a simple beam subject to a three-point symmetrical load. The area of uniform stress is small and concentrated under the centre loading point. For a three-point configuration there is the presence of a resultant vertical shear force everywhere in the beam except right under the mid-point force.

In a four-point test, the area of uniform stress exists between the inner span loading points. A much larger portion of the beam is at maximum stress which is necessary for non-homogeneous materials including timber and composites. With a four-point configuration the bending moment and maximum flexural stress are constant between the force application member. There is also no resultant vertical shear force in the area between the force application members [49].

2.8.1.1 Bending Test for Composite Materials

ASTM D7264 is the international standard for determining flexural properties of polymer matrix composite materials. The three and four-point loading test methods are illustrated below. For the four-point test the distance between the centrally located load points is half of the support span. The standard L/t ratio for specimens is 32:1, the standard specimen thickness is 4mm, and the standard specimen width is 13mm, with the specimen length being about 20% longer than the support span. However, L/t ratios of 16:1, 20:1, 40:1 and 60:1 may also be used. The crosshead speed for testing should be 1.0mm/min [49].

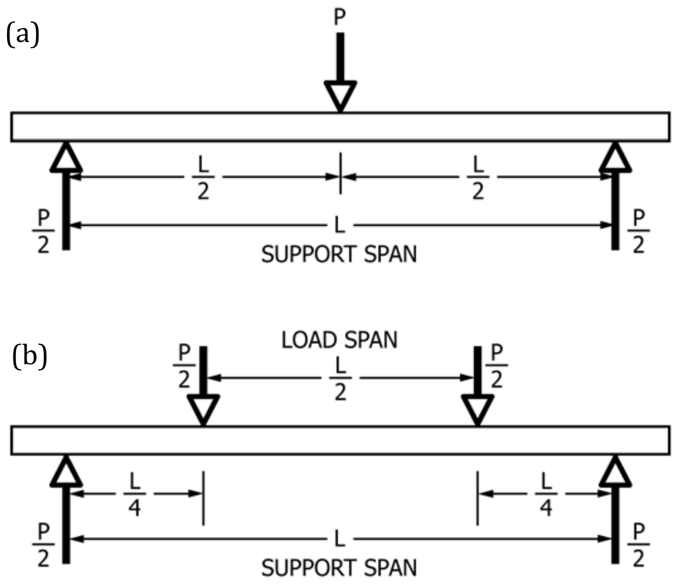


Figure 5 - Composite material bending test setup. (a) 3-point bending and (b) 4-point bending [49].

2.8.1.2 Bending Test for Structural Panels

ASTM D3043 is the international standard for determining flexural properties for strips cut from structural panels including plywood and composites of veneer and of wood-based layers. Method B of this standard is similar to the four-point test outlined in ASTM D7264 where the distance between the centrally located load points is half of the support span. It is recommended that the span is at minimum equal to spacing between the load points plus 48 times the specimen thickness if the principal direction is parallel to the span [51].

2.8.1.3 Bending Test for LVL

AS 4357.0 and AS 4357.2 set out the Australian standard for determining bending stiffness and strength of LVL products. The support span should be set at 18 times the specimen thickness and loading points are set at 1/3 points of the test span as specified in Figure 6. The total specimen span should be at minimum 20 times the thickness. The testing speed should be not greater than 0.18 t mm/min where t is the specimen thickness. The modulus of elasticity should be calculated using the following equation:

$$E = \frac{23\,\ell_s^{\,3}\,\Delta P}{108\,b\,d^3\,\Delta y} \quad \text{(MPa)} \tag{8}$$

where

ℓ_s = support span (mm)
ΔP = change in load (N)
d = specimen thickness (mm)
b = specimen width (mm)
Δy = change in deflection (mm)

Note that ΔP and Δy increments should be taken from the linear portion of the load-deflection curve.

For determination of the bending strength the same testing method is used and the beam loaded until failure. The bending strength should be calculated with the following equation where P_{max} is the failure load (N) [44].

$$R = \frac{P_{\max}.\,\ell_s}{b\,d^2} \quad \text{(MPa)} \tag{9}$$

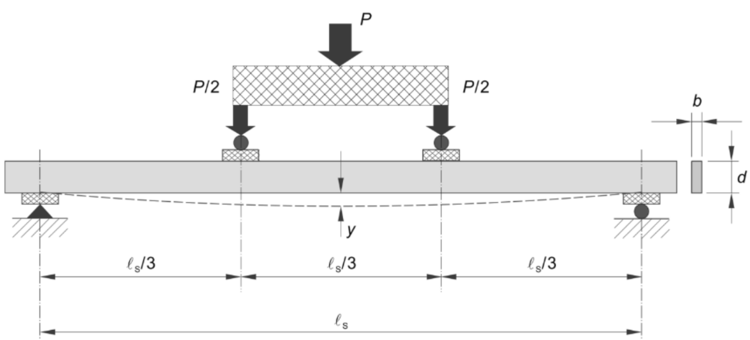


Figure 6 - Standard test configuration for measurement of bending strength and modulus of elasticity for LVL [44].

2.8.1.4 Bending Test for Stiffness of Scaffold Planks

AS1577:2013 is the Australian standard for scaffold planks. The bending test setup is shown in Figure 7 where a 100x100mm square block is used for loading at the midspan of the plank. The supports should be 48.3mm outside diameter steel tube. Duty ratings for different scaffold plank categories are listed in Table 7.

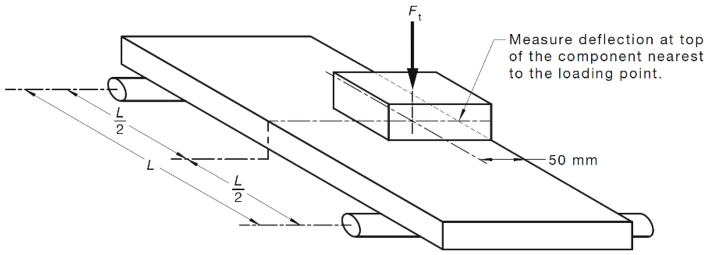


Figure 7 - Scaffold plank bending test setup [52]

Table 7 - Duty load categories for scaffold planks [52]

Duty Category	Minimum bay width (mm)	Total bay load (kN)	Working Load Limit (WLL)	
			kN	kg
Light Duty	450	2.2	1.69	173
Medium Duty	675	4.4	2.25	230
Heavy Duty	900	6.6	2.53	258

The working load limit (WLL) in kN is calculated as follows:

$$\mathrm{WLL} = Q \times b/(2/3 \times W) \tag{10}$$

where

Q = total bay load (kN)
b = width of plank (mm)
W = minimum bay width (mm)

For stiffness testing, the plank is first preloaded to 100N for 1 minute before increasing the load to the WLL and holding for 5 minutes. The deflection is measured at the midspan and calculated as the difference between the deflection under preloading and the WLL. This deflection must be below the support span/100 to a maximum of 30mm [52].

2.8.1.5 Bending Test for Structural Plywood

AS2269.2:2012 outlines the test methods for stress grading of plywood panels through four-point bending tests as shown in Figure 8.

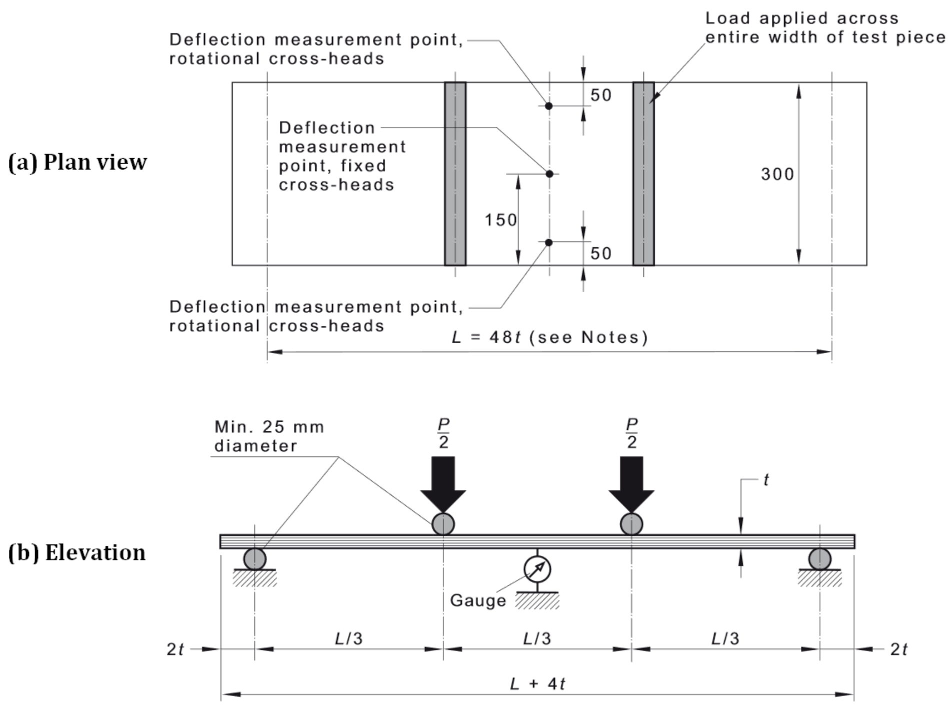


Figure 8 - Bending stiffness test configuration for structural plywood [53]

The modulus of elasticity is calculated using the following equation:

$$E = \frac{23\,L^3}{1296\,I_{\text{par.}}}\left(\frac{P'}{\Delta}\right)\ \text{MPa} \tag{11}$$

where

L = support span (mm)

P'/Δ = initial gradient of the load-deflection curve (N/mm)

I_{par} = second moment of area for the face grain parallel to the span (mm^4)

The second moment of area I_{par} is calculated using only plies in the 0° direction using parallel axis theorem [46]. This significantly decreases the calculated I_{par}, however the transverse modulus of the timber veneers is very small compared to its longitudinal modulus, making the assumption only a small underestimation.

2.8.2 Tensile Tests

2.8.2.1 Tensile Test for Composite Materials

ASTM D3039 is the international standard for determining in-plane tensile properties of polymer matrix composite materials. The specimen should be a thin, flat strip of constant rectangular cross-section. The design of test specimens remains largely an art rather than a science with no industry consensus on how to approach the engineering of the gripping interface, however some requirements are outlined in ASTM D3039. The specimen should be at least 250mm in length overall, at least 1mm in thickness, and 15mm in width for 0° unidirectional composites. For constant head-speed tests, a displacement rate of 2mm/min is standard. The specimen should contain a sufficient number of fibres in the cross-section to be statistically representative of the bulk material. It is also recommended that at least five specimens are tested for each test condition to ensure statistically significant data [54].

2.8.2.2 Tensile Test for LVL

AS 4357.2 sets out the Australian standards for determining the modulus of elasticity in tension for LVL panels. The length of the test specimen should be sufficient to provide a test length, clear of the machine grips of at least nine times the larger cross-section dimension when tested in self-aligning grips. When testing with non-aligning grips, the length between grips should be 2250 + 7.5d mm but not greater than 30d, where d is the greater cross-sectional dimension. The strain rate should not be greater than 5 x 10^{-6} mm/mm/s [55].

2.8.3 Summary of Testing Procedures

The important testing parameters are listed in Table 8 for four-point bending tests, and in Table 9 for tensile tests.

Table 8 - Four-point bending test parameters

4-Point Bending Test	Standard L/t ratio	Loading span	Crosshead speed (mm/min)
Composite Materials	32:1	L/2	1.0
LVL panels	20:1	L/3	<0.18 t

Table 9 - Tensile test parameters

Tensile Test	Minimum overall length (mm)	Crosshead speed
Composite Materials	250	2 mm/min
LVL panels	2250 + 7.5d	Strain rate <5 x 10^{-6} mm/mm/s

3 Hemp Fibre Composite Development

Development of a NFRP composite is proposed as a new method of strengthening and stiffening structural laminated timber products. It is expected that a NFRP composite sheet can be developed with a modulus and strength significantly higher than low-grade timber species. The NFRP is to be in a veneer-like form, similar to timber veneers, and added at or close to the outer plies of a timber laminate. By placing the stiffer composite veneers far from the neutral axis, the performance of laminates in bending is expected to be greatly improved, allowing for use of lower grade timber for the remaining plies.

3.1 Manufacturing Techniques

In order to produce a low cost composite product, a manufacturing technique requiring minimal processing of the fibres is proposed. Dried stems of industrial hemp were attained, shown in Figure 9, for use in developing natural fibre composite sheets.

Figure 9 - Industrial hemp stems as-received for use in natural fibre composite sheet

Typical fibre processing methods include decortication and carding to remove the outer bast fibres from the non-fibrous material and align the fibres in a single direction. Numerous chemical treatments are also used to aid in processing and remove unwanted constituents from the fibres. These processes impose significant added costs to the as-received plant stems and overall composite material. The proposed minimal processing technique skips the major decortication step and utilises the inherent natural fibre alignment of the hemp stems. Chemical treatments are also often used to improve the fibre-matrix interface. This adds a further expense to NFRP composite products and may be a further limiting factor to the commercial use of natural fibres in addition to their non-uniform properties and lack of repeatability. By avoiding these processing steps a lower-cost composite material can be produced however its mechanical properties must still be comparable to those of traditional NFRP composites.

Two manufacturing methods are used process the as-received hemp stems and create a unidirectional composite sheet. In both methods a press is used to aid in processing of the stems, as well as a shaping tool to compact the fibres and matrix material into a veneer-like sheet.

In these processes no fibre washing steps are performed, including washing with water. Washing would likely be able to improve the fibre-matrix interface by removing dirt and other impurities from the fibre surface.

3.1.1 Splitting and crushing stems

The first method involves splitting the stems longitudinally using a blade into four segments before crushing them in a press to produce thin, compacted stem segments which include the inner non-fibrous stem material. The stalks are then laid unidirectionally and excess resin is poured over the stems. The wet layup is then pressed between two stainless steel platens in a press until the resin has cured. This process is shown in Figure 10 for a sheet used in tensile testing. The segmented stems were crushed in the press to 2-3MPa before laying and the composite sheet pressed at an elevated temperature of 60°C to accelerate curing of the epoxy resin.

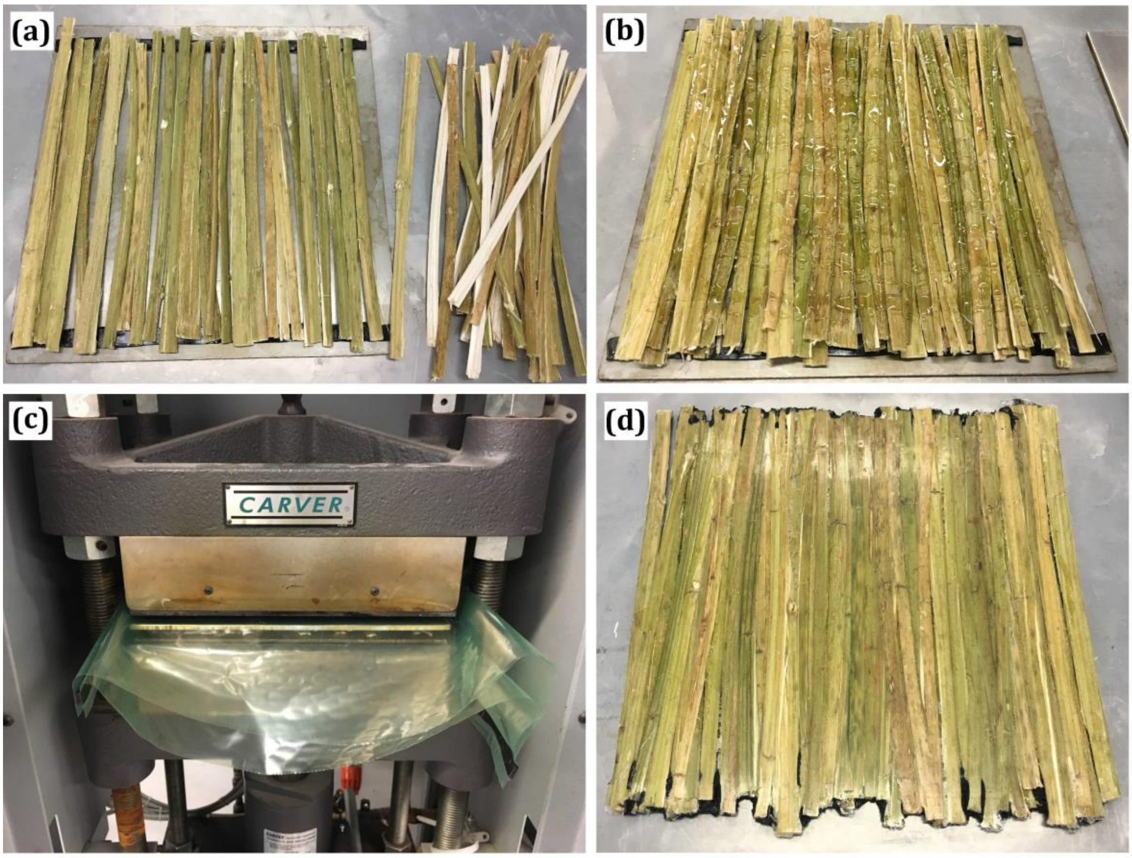


Figure 10 - Composite processing steps for splitting and crushing stalks. (a) Unidirectionally laying split and crushed stems on steel plated with the aid of putty. (b) Pouring resin evenly over stems. (c) Bagging the wet layup and pressing at 2MPa and 60°C. (d) The cured composite sheet before trimming.

Importantly the split stems were laid in two layers. All hemp stems have some level of curvature which leaves gaps in the layup if laid in a single layer filled only by resin. This is problem is shown in Figure 11 (b) where there are large gaps between the stems segments. This sheet will have significantly reduced transverse properties to the two-layer sheet in Figure 11 (a), as well as lower axial properties due to the larger fibre volume fraction. Overall, Figure 11 demonstrates the importance of both crushing the split stems to obtain a compacted stem, as well as laying them in more than a single layer. This has produced a composite sheet with a thickness of approximately 3-3.5mm.

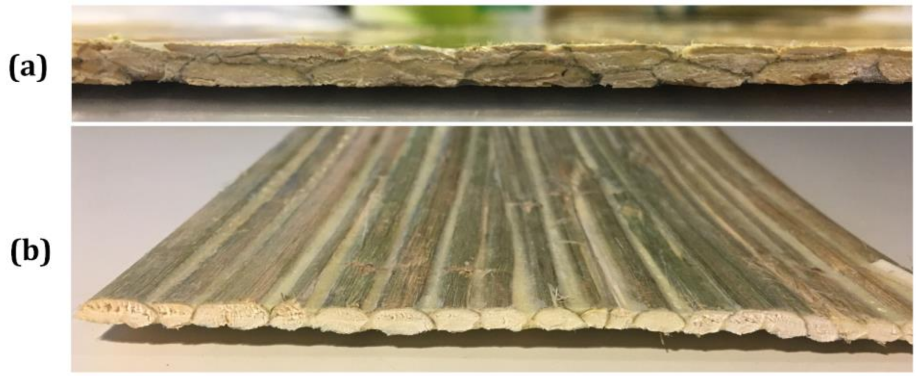


Figure 11 - Cross section of hemp composite sheet. (a) Split and crushed stems laid in two layers. (b) Only split stems laid in single layer.

The major issue associated with this process is the uneven cross-sectional thickness of the sheet due to the large distribution of stem sizes and curved stems adding more than two layers in some sections. Porosity is also an important issue for this method. Air may be unable to escape from within the press and large pores are observed especially in areas on differing cross-sectional thickness.

3.1.2 Stripping outer bast fibres

The second method required further processing of the as-received stems, aiming to use only the outer bast fibres of the stem by stripping it from the woody centre. This is far different from a traditional decortication process as the natural alignment of the fibres is not broken. In this method the stems are crushed in a press to approximately 2MPa. Crushing is required to aid in removing the outer fibres. Figure 12 shows the crushing process where the woody centre of the stem fractures into many sections and detaches from the outer fibres in some areas.

Figure 12 - Intermediate crushing steps of hemp stems. (a) Before crushing. (b) Crushing at ~0.5MPa. (c) Complete crushing at 2MPa.

After crushing, the fibres far more readily peeled from the inner xylem and pith sections of the stem. Figure 13 shows the fibres being cleanly stripped from the hemp stem.

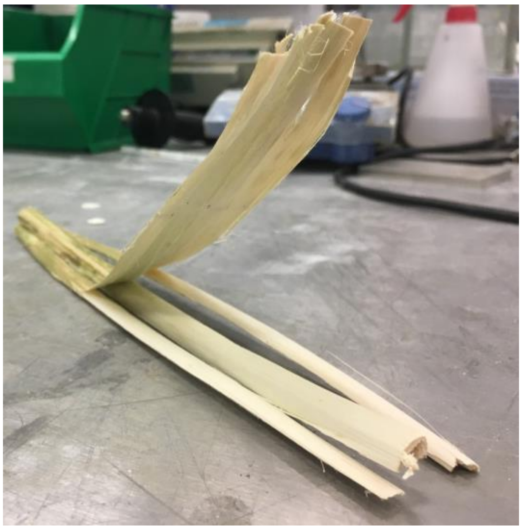


Figure 13 - Stripping the outer bast fibres from the hemp stem

To create the composite sheet, the fibres were laid unidirectionally, similar to the splitting and crushing method, before distributing excess resin over the fibres and pressing between two platens. Figure 14 shows the cured hemp/epoxy composite before trimming. The major drawback of this method is the time consuming fibre stripping process which may be difficult to modify for an automated, commercial process. A large amount of stem material is also required to produce a practical sheet thickness. The sheet in Figure 14 was made with 2-3 layers of fibre material in all areas resulting in a sheet thickness of approximately 1mm.

Figure 14 - Hemp/epoxy composite sheet using method of stripping outer bast fibres. (a) top surface. (b) bottom surface.

3.2 Physical Properties of Hemp Composite Sheets

During processing of the hemp composite sheets, the yield of the outer bast fibres from the hemp stalks was calculated as approximately 22.8% by mass. Combined with the inherently thin sheets produced using only the bast fibres, the low yield contributes to the greatly increased cost of the Hemp bast/epoxy composite as shown in Table 10. Costs per unit volume and mass are also listed using approximate cost ranges and measured mass and volumes of the different composite sheets. The fibre weight fraction of the composite sheets was also calculated and estimated ranges are shown in Table 11.

Table 10 - Physical properties of hemp composite materials and constituent materials

Material	Density ρ (g/cm^3)	Cost per m^3 (AUD/m^3)	Cost per kg (AUD/kg)
Raw hemp stalk	0.325	54.17-108.3	0.167-0.33
Hemp bast fibres	-	0.73-1.46	0.73-1.46
Epoxy resin	1.1-1.4	2530-3640	2.3-2.6
Hemp stem/epoxy	0.648	422-550	0.65-0.85
Hemp bast/epoxy	1.32	1772-2517	1.34-1.90

Table 11 - Estimated fibre weight fraction of composite for different manufacturing methods

Manufacturing method	Fibre weight fraction W_f (%)
Splitting and crushing stem	72.4 - 82.2
Stripping bast fibres	57.3 - 64.9

3.3 Tensile Testing of Hemp Composite Sheets

3.3.1 Preparation of test specimens

Tensile testing was performed on four individual hemp composite sheet samples. Each square-shaped sheet was cut into rectangular test specimens with approximate dimensions: 200mm length and 25mm width. Thickness of the specimens was measured in 6 places and width at 3 locations along each specimen and averaged. The specimens were then painted white using spray painted before applying a random black speckle pattern with a spray can for use with Digital Image Correlation (DIC). Figure 15 shows test specimens before and after painting.

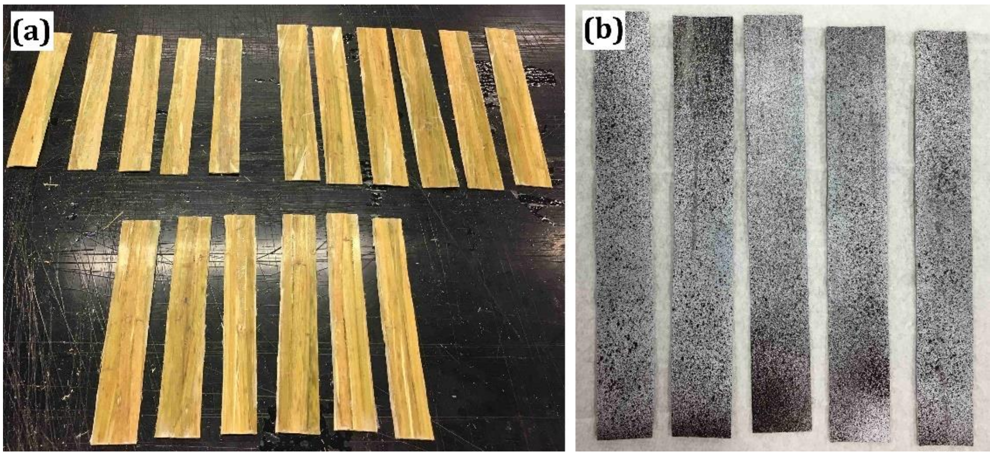
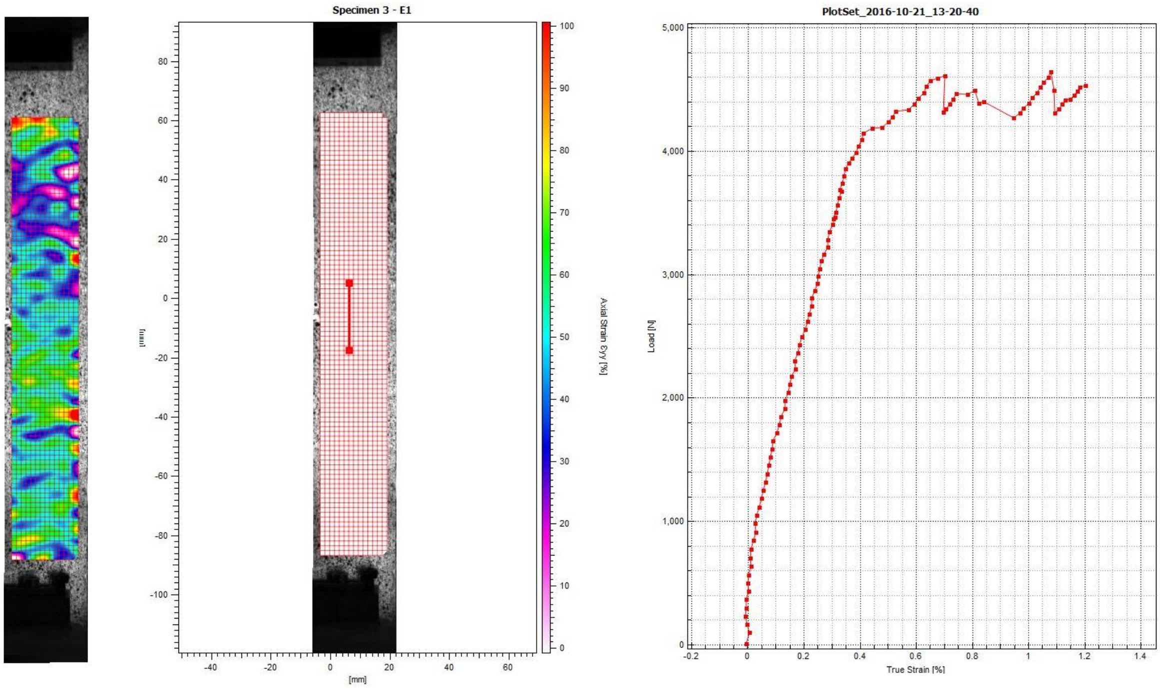


Figure 15 - Preparation of hemp composite tensile specimens. (a) Cutting into rectangular specimens. (b) Painting a random speckle pattern.

3.3.2 Testing procedures

Tensile testing was performed primarily to obtain tensile modulus and tensile strength values for the hemp composite sheets in order to assess their potential use as part of a timber laminate. Due to the high inhomogeneity of the thickness and composition of the composite phases across its width, Digital Image Correlation (DIC) was used to accurately analyse the stress state in tension and visualise the distribution of strain within the specimens. This allows for an accurate axial strain reading to be recorded after data processing with DIC software. Appendix A shows a composite specimen being tested. Figure 16 shows the DIC data processing procedure used for all tensile tests. A virtual strain gauge was placed longitudinally on the specimen in a region of relatively uniform strain to retrieve strain data.



(a) (b) (c)

Figure 16 - Digital Image Correlation (DIC) processing procedure. (a) strain map of test specimen. (b) placement of virtual strain gauge. (c) load-extension plot using strain data from virtual strain gauge.

3.3.3 Tensile testing for splitting and crushing method

Initial testing was performed on a hemp composite made using a single layer of crushed hemp stems with a matrix of Ampreg 22 epoxy with fast hardener. This was cured in the press at 60°C and 2MPa for 1 hour. Figure 17 shows a sample of the initial composite trial.

Figure 17 - Initial hemp stem/epoxy composite trial. A large gap is observed between stems segments as well as significant porosity in the epoxy resin.

The test results in Table 12 and Figure 18 show an initial high stiffness region at very low strains. This decreases to a near-constant tensile modulus after approximately 0.1% strain which is maintained until fracture. There is an initial high stiffness region at very low strains. This decreases to a near-constant modulus after approximately 0.1% strain which is maintained until fracture. Based on these test a base design modulus of approximately 16GPa was deduced.

Table 12 – Initial Hemp/Epoxy composite tensile test results

Specimen code	Tensile Modulus E_1 (GPa)			Failure Stress σ_f (MPa)	Elongation at break (%)
	0.001 – 0.01% strain	0.01 – 0.1% strain	0.1 – 0.3% strain		
A	36.17	17.53	13.84	60.22	0.309
B	32.52	21.24	17.19	91.69	0.561
C	32.67	15.71	13.29	72.15	0.694
D	29.75	17.91	13.77	90.5	0.679
Average	32.78	18.10	14.52	78.64	0.561
Standard Deviation	2.28	2.00	1.55	13.16	0.15

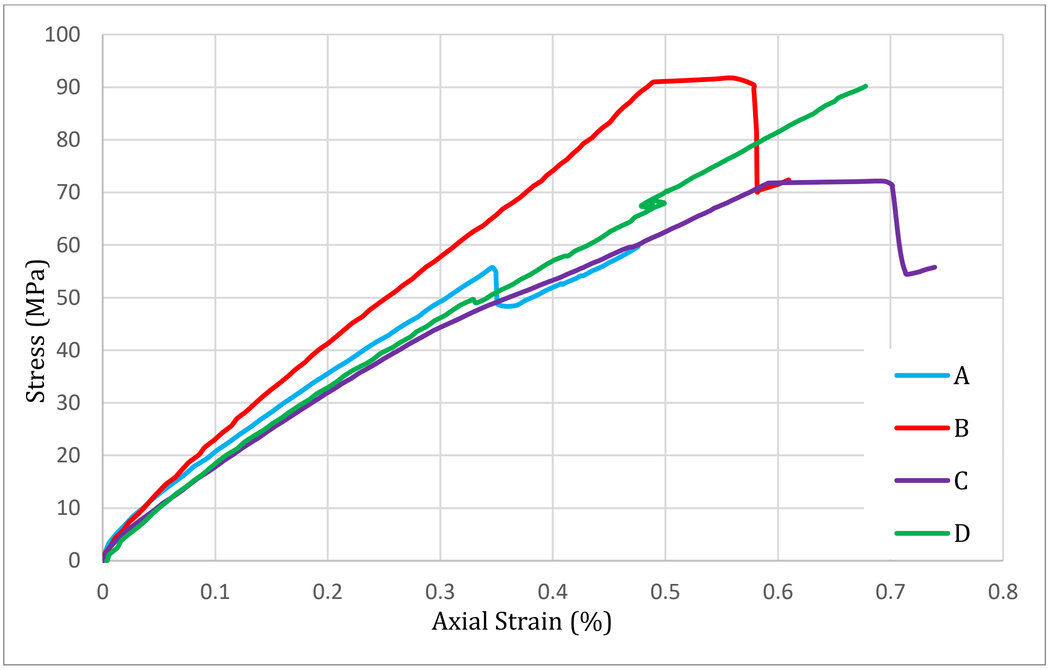


Figure 18 - Stress-strain curves of preliminary tensile testing of hemp/epoxy composite with DIC

On failure, the outer bast fibres separated from each other into thin filaments. This is believed to occur after a single fibre breaks longitudinally, leading to increased stress on the surrounding fibres which fail chaotically. Longitudinal cracks formed in areas where the epoxy resin was the prevalent phase. The outer bast fibres generally stayed intact and instead the inner woody section of the hemp stems fractured. This indicates that the bast fibres may be significantly stronger. The bast fibres also tended to separate completely from the inner stem on failure. This is a result of the weak bonding between the bast fibres and inner stem and differences in elongation at failure between them. Some samples fractural locally but were still able to support additional load with on a minor decrease in slope of the stress-strain curve. This is clearly demonstrated in Sample A where the stress drops suddenly by 6-7MPa at 0.35% strain and continues to increase with a similar slope.

Table 13 and Figure 19 show test results for the hemp/epoxy prepared as pictured in Figure 10. This uses West System 105 epoxy resin with 206 slow hardener, pressing at 44°C and 2MPa for 4 hours. The design modulus is calculated up to 0.15% strain for all specimens. This is expected to be at or below a typical strain level for typical loading of structural laminated timber products. This gives an average modulus of 18.37GPa and failure stress of 69.83MPa.

Table 13 - Hemp/Epoxy composite tensile test results for splitting and crushing method with two layers of hemp stems

Specimen code	Tensile Modulus E_1 (GPa) up to 0.15% strain	Failure Stress σ_f (MPa)	Elongation at break (%)
S1	19.45	62.35	0.402
S2	18.26	79.22	0.724
S3	21.26	70.88	0.578
S4	15.88	79.73	0.763
S5	17.00	56.97	0.563
Average	18.37	69.83	0.606
Standard Deviation	1.88	9.04	0.13

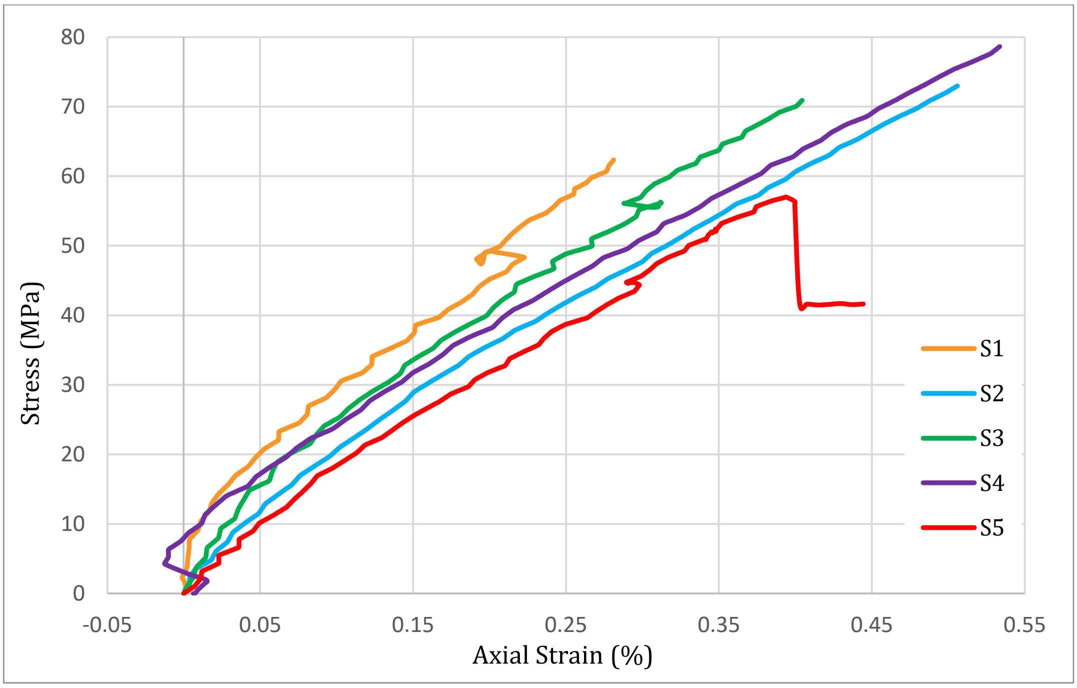


Figure 19 - Stress-strain curves for hemp/epoxy composite with DIC. Specimens made using splitting and crushing method.

The distinct waviness of the stress-strain curves is attributed as an artefact of the use of DIC. This is not present in preliminary testing in Figure 18 despite the same testing procedure being used. It is believed that this is due to the speckle pattern used for DIC measurement being painted on the bast fibre side of the specimens for the second test in Figure 19, but on the opposite side for preliminary testing. The bast fibres are expected to undergo a more chaotic and non-uniform strain response to tensile loading, leading to the distinct waviness of the stress-strain curves.

Figure 20 shows a typical failure mechanism of the hemp composite. Longitudinal cracks form at interfaces between separate hemp stalks where a thin layer of epoxy resin is present. Failure of the bast fibres also occurs on the at the surface of the sheet.

Figure 20 - Longitudinal cracking of the hemp/epoxy composite under tensile load, Cracking occurs at the interface between separate hemp stalks.

3.3.4 Tensile testing for stripping bast fibres method

Two hemp composite sheets were tested using only the outer bast fibres of the hemp stems. The first was made using Jowapur 685.09-A15 single component polyurethane adhesive, pressing at room temperature for 45 minutes. This sheet is shown in Appendix B. The polyurethane matrix in this sample is highly porous with a foam-like appearance. This is likely due to foaming of the polyurethane on hardening due to the chemical reaction releasing carbon dioxide gas. Stress-strain curves shown in Figure 21. This sheet has a design modulus of 24.71GPa and failure stress of 132.66MPa.

The hemp bast/epoxy sheet was made using West System 105 epoxy resin with 206 slow hardener, pressing at 60°C and 2MPa for 1.5 hours. This was by far the highest performing composite sample, reaching am average failure stress of 143.7MPa with an average modulus of 37.73GPa.

Table 14 - Hemp bast/Epoxy composite tensile test results with polyurethane and epoxy matrix

Hemp/Polyurethane			
Specimen code	Tensile Modulus E_1 (GPa) up to 0.15% strain	Failure Stress σ_f (MPa)	Elongation at break (%)
P1	25.25	143.98	1.215
P2	25.56	133.04	1.070
P3	18.31	101.22	1.089
P4	29.71	152.40	0.623
Average	24.71	132.66	0.999
Standard Deviation	4.09	19.41	0.22
Hemp/Epoxy			
Specimen code	Tensile Modulus E_1 (GPa) up to 0.15% strain	Failure Stress σ_f (MPa)	Elongation at break (%)
E1	32.43	151.35	0.701
E2	32.39	139.42	0.549
E3	35.74	132.54	0.642
E4	40.89	118.23	0.530
E5	40.05	143.70	0.615
E6	44.80	185.00	0.685
Average	37.72	145.04	0.620
Standard Deviation	4.58	20.60	0.06

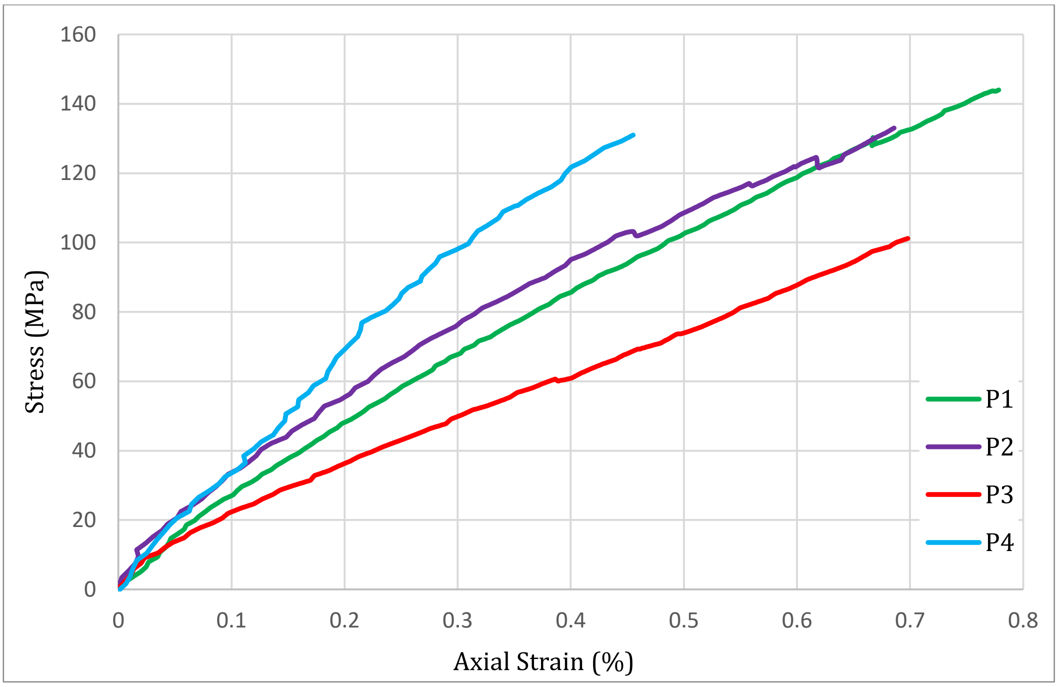


Figure 21 - Stress-strain curves for hemp bast/polyurethane composite with DIC

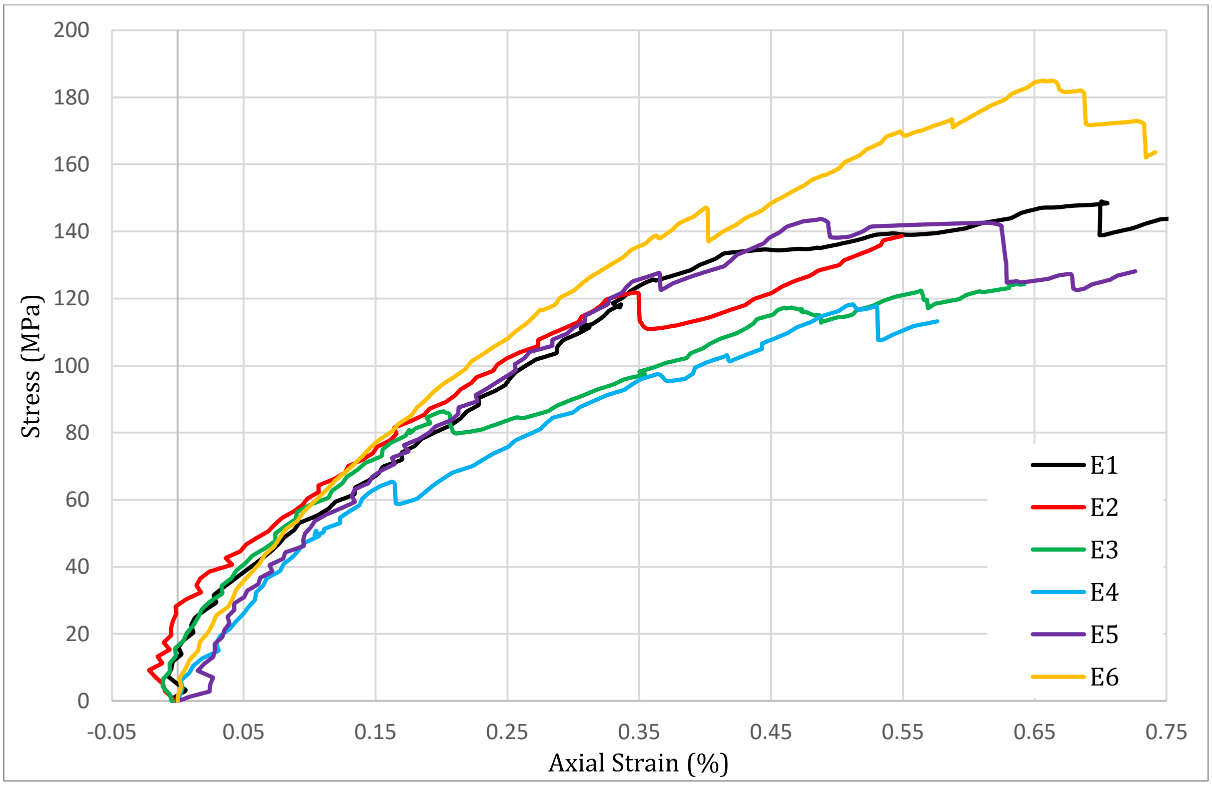


Figure 22 - Stress-strain curves for hemp bast/epoxy composite with DIC

Figure 23 shows a hemp bast/epoxy specimen after testing. Failure typically begins with fracturing of a single fibre and separation of fibrils into thin filaments. This leaves distinct longitudinal cracks on the sheet surface, parallel to the fibre direction. If loading is continued, more cracks are formed and fibres begin to completely pull out.

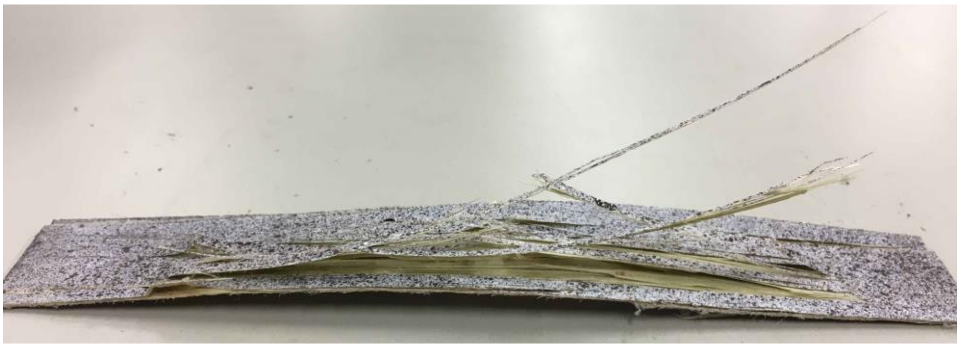


Figure 23 - Typical failure of the hemp bast/epoxy sheet in tensile testing through longitudinal fibre fracture, longitudinal splitting of bast fibres

3.4 Summary of tensile test results

Table 15 gives a summary of the averaged mechanical properties for each of the tested hemp composite samples.

Table 15 - Summary of averaged mechanical properties of each composite sample

Sample	Tensile Modulus E_1 (GPa) up to 0.15% strain	Failure Stress σ_f (MPa)	Elongation at break (%)
Split and crushed hemp/Epoxy	18.37	69.83	0.617
Stripped hemp bast/PU	24.71	132.66	0.999
Stripped hemp bast/Epoxy	37.72	145.04	0.620

3.5 Discussion and significance of tensile test results

Tensile testing has proven the concept of minimal processing manufacturing techniques able to produce thin, unidirectional-fibre composite sheets with high strength and high elastic modulus. Initial testing identified a base design modulus of 16GPa for a low quality hemp NFRP composite with relatively large gaps between unidirectionally laid hemp stems filled only by matrix material and high levels of porosity clearly visible in the matrix. All further testing produced significantly improved elastic moduli and generally higher strength. Strength of the hemp composite is critically dependent on flaws in the as-received stem due to branches in the stem, mechanical damage during harvesting and processing, and other naturally occurring defects. Because of this, a high variance in failure strength of the composite specimens is expected. However, in all cases, the composite specimens are able to carry further load after local fractures with a similar slope in the stress-strain curve.

As was previously discussed briefly in this section, no washing or chemical treatments were used to attempt to improve the fibre-matrix interface of the composites. As discussed in Section 2.3.3.1, modifications to the fibre surface through caustic treatments aimed at reducing lignin and increasing hydroxyl groups on the fibre surface have not been proven to be effective. However, it is likely that simply washing with water and drying would have been a useful step in removing foreign material from the fibre surface which would act as a barrier, preventing proper bonding of the fibres and matrix. Still, the most important issue inherent to natural fibres is the non-uniformity of the fibre surface, leading to areas of good and poor interfacial bonding. This can lead to areas of stress concentration and is a major challenge for the production of natural fibre composites with highly repeatable properties [11].

Comparing the tested composite sheets to other reported values for UD NFRP composites in literature highlights the potential benefits of minimal processing of natural fibres. Table 4 lists maximum reported modulus and strength values of UD NFRP composite made using traditional fibre processing methods including decortication and spinning into a yarn. The average modulus for the hemp bast fibre/epoxy composite is 34.7% higher than that of reported flax and hemp composites and at an unquestionably lower cost. The average tensile strength for the hemp bast/epoxy composite of 145MPa is significantly lower than the highest reported strength of other composites which can be attributed to the high influence of natural defects in the unprocessed stems. This is the major downfall of using minimal processing methods as fibre yarns, tows and woven mats will have much smaller defects and therefore more repeatable properties.

The significance of the test results in regards to their use with laminated timber constructions can be evaluated by direct comparison to standard stress grades for plywood and LVL detailed in Table 5. Table 16 lists the corresponding stress grade for the averaged modulus and tensile strength of each hemp composite sample. Note that F11 and F14 grades are most commonly used for structural applications.

Table 16 - Comparison of hemp composite test results to plywood stress grades

Sample	Tensile Modulus E_1 (GPa)	Corresponding Stress Grade	Tensile Strength σ_f (MPa)	Corresponding Stress Grade
Split and crushed hemp/Epoxy	18.37	F22	69.83	F34
Stripped hemp bast/PU	24.71	F34	132.66	F34
Stripped hemp bast/Epoxy	37.72	F34	145.04	F34

As the characteristic modulus and strength properties are rated for laminates, it is difficult to fully predict the stiffening and strengthening capabilities of the hemp composite when incorporated into a timber laminate; this type of assessment is the aim of Section 5 of this report. However, it does indicate strong potential improvements to both strength and stiffness. All tensile strength values for the hemp composites are far above 54MPa, the corresponding value for the highest stress grade. Hemp composites using only the outer bast fibres also far surpassed the corresponding modulus value of 21.5MPa for the maximum stress grade.

Aluminium is commonly used for similar applications as structural laminated timber, especially in scaffold boards, requiring a minimum tensile strength of 160MPa [52]. The average tensile strength of the tested hemp bast/epoxy composite is within 10% of this value and the average modulus is over half a typical aluminium modulus of 70GPa. Typical aluminium grades for these applications comes at an estimated cost of 6,500AUD/m^3, three times the estimated material cost of the hemp bast composite. The hemp bast composite's modulus also approaches that of UD glass fibre composites, even further demonstrating the significance of the test results and widening the potential applications of this material [16].

4 FE Model Validation

In order to assess the influence of adding hemp composite sheets to different laminated timber products, a finite element model was created using ANSYS Composite PrePost (ACP). Before using this for direct predictions of laminate properties, the model was validated using Laminated Veneer Lumber (LVL) tested in 4-point bending. 4-point bending is performed preferentially over 3-point bending to place a larger portion of the specimen under maximum stress which is often necessary for non-homogeneous timber products as discussed in Section 2.8.1.

4.1 Production of LVL Specimens

A brief discussion of the LVL manufacturing steps will be provided and photographs of each step are shown in Appendix C.

Three LVL samples were produced using selected timber veneers supplied by the Queensland Department of Agriculture and Fisheries (DAF) Salisbury Research Facility. Before gluing and pressing the veneers into laminates, they were kept in a 12% moisture conditioning room at 23°C for 1 week. This was done to ensure an adequate moisture content in the timber which is required by the polyurethane adhesive. PURBOND HB S309 adhesive was used to glue to veneers. This is a single-component polyurethane adhesive specifically for the manufacturing of engineered wood products. It cures under the action of air humidity and moisture in the timber. During hardening some foaming occurs due to the chemical reaction releasing carbon dioxide gas [56].

Prior to pressing, the modulus of elasticity of each veneer was measured using Beam Identification by Non-destructive Grading (BING) software. This measures the timber modulus through its response to longitudinal vibrations [57]. A microphone was positioned at the far end of the veneer and a small hammer was used to tap the opposite side. A PicoScope 4000 Series oscilloscope was used to process the data with BING software. In order to calculate the timber modulus, the mass and dimensions of each veneer was also measured. Table 17 lists the measured modulus of veneers used in LVL sample.

Table 17 - Measured modulus of timber veneers for LVL model validation

Layup	Thickness (mm)	Measured Modulus of Elasticity E (GPa)						
		Ply number						
		1	2	3	4	5	6	7
A	20.51	16.861	22.279	20.446	19.624	20.525	21.958	17.775
B	19.96	15.862	15.042	17.312	13.907	15.788	15.755	16.647
C	13.06	17.653	15.877	14.533	16.291	18.560	-	-

The polyurethane adhesive was applied evenly between each veneer at a spread rate of 180g/m^2 and the layups were pressed at 1MPa for 75 minutes. The technical datasheet (TDS) for this adhesive stipulates a maximum allowable open time of 30 minutes before pressing is begun. Laminates A and C were assembled below the maximum time after 25 and 27 minutes respectively, however laminate B was not pressed until 33 minutes after gluing was commenced.

This may make the data collected from laminate B invalid, however the adhesive was still noticeably 'tacky' immediately prior to pressing, indicating that is was still useable.

Each LVL laminate was then cut using a Waterjet cutter to produce specimen sizes corresponding to a L/t (length/thickness) ratio above 20, consistent with AS 4357.2 for four-point flexural testing of LVL beams.

4.2 Flexural Testing of LVL Specimens and Comparison to FE Model

Testing was performed in accordance with AS 4357.2, however only the cross-head movement was recorded, without the use of a deflectometer. 25mm rollers were used for all loading and support points with a crosshead speed of 2mm/min. Load and deflection data was recorded for each specimen which was compared to identical, but idealised FE models for each laminate. Figure 24 shows intermediate loading of an LVL specimen. As expected there is a smooth curvature along the beam. First failure occurs at the bottom ply where the maximum tensile stress is applied.

(a)
(b)

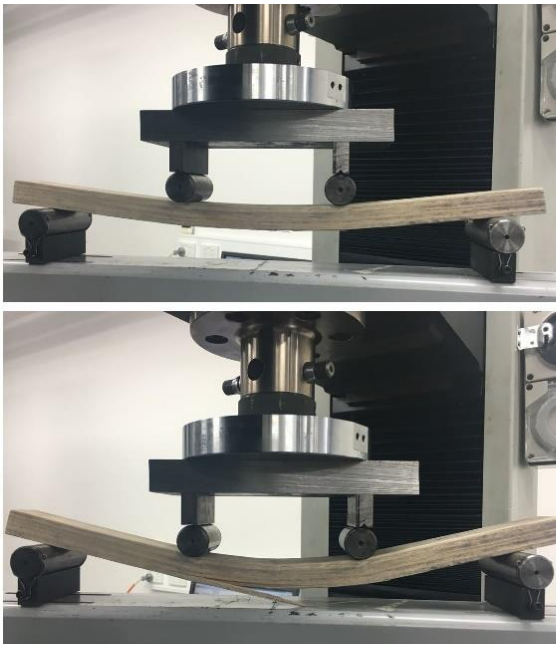


Figure 24 - Four-point flexural testing of LVL specimen. (a) Low deflection. (b) First fracture of the specimen at the bottom ply.

The FE model idealises the loading and support rollers line loads and assumes perfect bonding between plies. Because a deflectometer was not used during testing, the deflection of the FE model was recorded at the load points as shown in Figure 25. Also because of this, the modulus of the timber laminates could not be easily and accurately calculated. Therefore, load-deflection curves were compared instead of stress-strain curves.

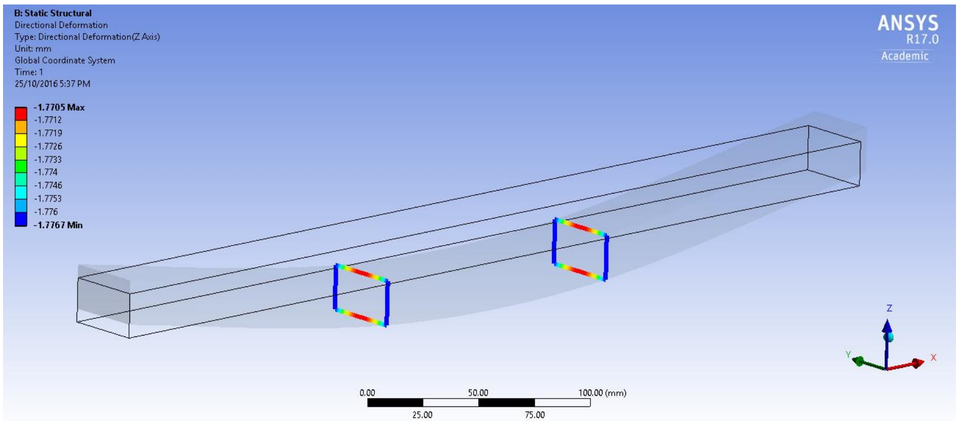


Figure 25 - ANSYS ACP model of LVL plank for model validation. Deflection is calculated at the load points.

In order to make the FE model more realistically simulate the bending performance of the timber laminates, 0.25mm gluelines were added between each ply of an isotropic materials with 1GPa modulus and a Poisson's ratio of 0.316. This was thought to be a reasonable glue thickness as the actual glueline is expected to be approximately 0.1mm in thickness, up to a possible maximum of 0.3mm as stated in the TDS for the adhesive used [56]. To maintain the total thickness of each laminate, gluelines were added assuming proportional reduction in thickness of each veneer. Figure 26 shows an example layup plot and stress plot for Sample C under 4-point bending, showing the addition of gluelines between plies.

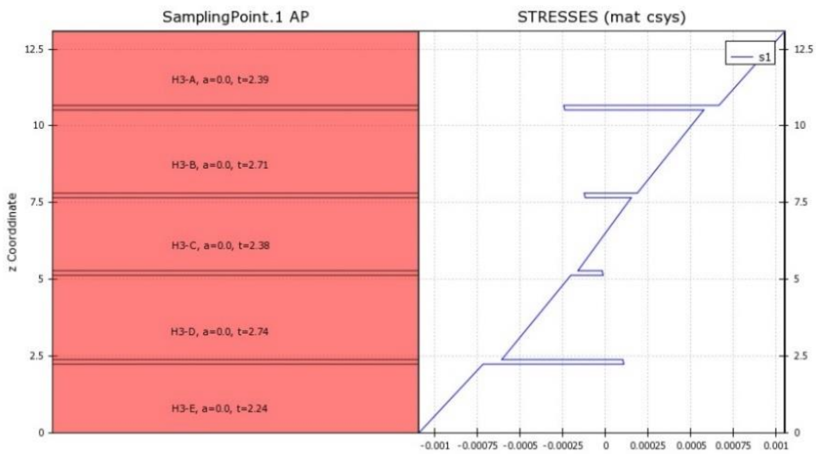


Figure 26 - Layup plot and stress plot of LVL specimen under 4-point bending in FE model showing the addition of gluelines

FE results were compared directly to the measured load-extension curves as shown in Figure 27 with the initial slope of FE models both unmodified and with gluelines added. Table 18 and Table 19 compare initial slope results numerically.

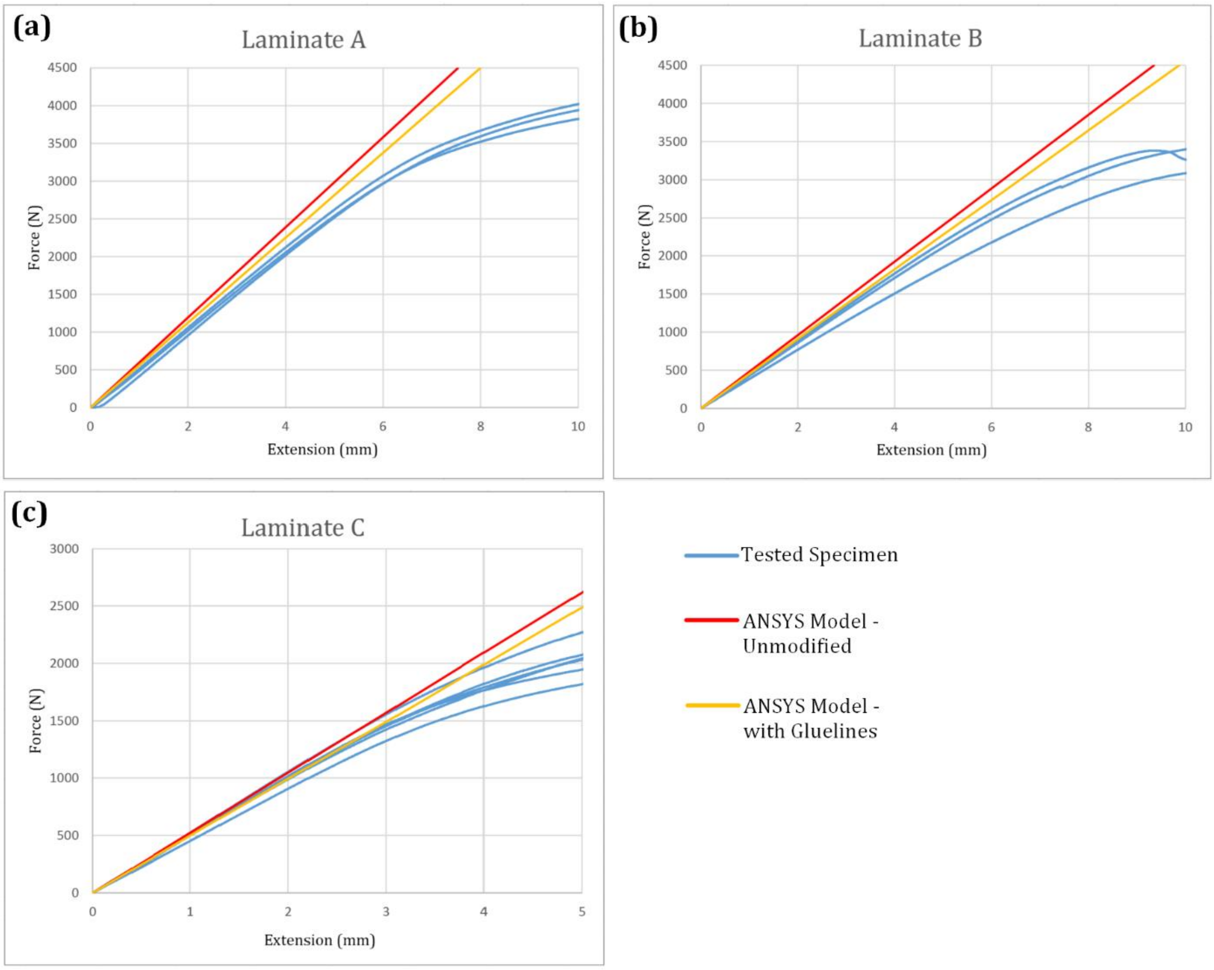


Figure 27 - Validation process of ANSYS ACP model comparing force-extension curves of tested specimens and model predictions with the addition of gluelines. (a) Sample A. (b) Sample B. (c) Sample C.

Table 18 - Initial force-extension slope of tested LVL specimens and FE models

Specimen	**Initial Force-Extension slope**		
	Layup A	Layup B	Layup C
1	535.04	430.25	455.97
2	538.66	377.88	504.07
3	523.33	446.65	532.16
4	-	-	495.38
5	-	-	507.77
6	-	-	516.12
Average	532.34	418.26	501.91
ACP FE Result (unaltered)	597.09	481.38	523.49
ACP FE Result (with gluelines)	562.83	455.98	497.27

Table 19 - Comparison of FE models to tested specimens

	Layup A	Layup B	Layup C
% difference of ACP unaltered	+10.84	+13.11	+4.12
% difference of ACP with gluelines	+5.42	+8.27	-0.93

After addition of gluelines, the FE model predicted the initial force-extension slope in 4-point bending to be between -0.93% and +8.27% of the experimental slopes, however if Layup B is ignored due to the possibility of exceeding the adhesive open time, the maximum error is +5.42%. Errors can be largely attributed to the varying properties of timber which is inherently inhomogeneous. Different specimens taken at different areas of each laminate will have slightly different properties depending on local features of the timber. Other sources of error can be attributed to the experimental procedures, including the slight misalignment of timber veneers from 0° in the longitudinal direction. The BING software used to calculate assumed perfect alignment of the veneers and was programmed for longitudinal modulus determination. BING measurement also relied on a 'good' hit with the test hammer to produce reliable results, as well as adjusting the sampling frequency and voltage range of the acquisition device. The modulus of the timber veneers may also vary slightly over time and with environmental conditions. Finally, only three unique samples were produced which may not be enough to properly validate the FE model.

5 Cost-Performance Analysis

To assess the commercial feasibility of using hemp composites as part of a timber laminated products, a cost vs. performance analysis was completed for two specific timber products: scaffold planks and structural plywood flooring. In all cases the composite material is added at the outer plies where its contribution to bending stiffness of the laminate will be the highest. The validated FE model was used to determine accurate force-deflection responses for different laminate configurations. For simplicity, all analysis is performed for laminates with equal thickness plies unless stated otherwise.

5.1 Definition on Laminate Configurations and Ply Properties

Table 20 details the properties, including approximate costs, of each type of timber and hemp composite ply used for comparison. Appendix D details the orthotropic ply properties used for FE modelling. The transverse modulus is estimated as $E_1/30$ and the shear modulus G_{12} is estimated as $E_1/20$.

It was estimated that the cost per unit volume of the hemp composite using crushed stems is more expensive than softwood timber, but cheaper than hardwood timber with a high elastic modulus. The hemp composite using bast fibres was estimated as over twice as expensive as hardwood timber but with a much higher modulus. It should be noted that the hemp composite costs are purely estimates of material costs, not retail prices. Table 21 clarifies the different laminates that will be used for further analysis. The A+HS(3.5mm) and A+HB(1mm) configuration indicate that the outer composite plies are 3.5mm and 1mm respectively. These are approximate thickness values of the actual composite sheets that were produced. For all cases, the number in brackets refers to the outer ply thickness. For the manufacturing method used, hemp stem composite plies are not practically producible below a 0.9mm thickness for the hemp bast composite, or below approximately 3.2mm for the hemp stem composite, however through other methods such as cutting sheets from a larger hemp stem composite block may allow thinner sheets to be produced. However, this may face further manufacturing hurdles, especially in removing air trapped between adjacent stems.

Table 20 - Definition of ply names and properties for laminate analysis

Material	Ply code	Modulus E (GPa)	Density ρ (g/cm^3)	Cost per m^3 (AUD/m^3)	Cost per kg (AUD/kg)
Softwood Timber (Radiata Pine)	a	8	0.45	350	0.78
	b	10	0.45	400	0.89
Hardwood Timber	c	20	0.725	750	1.05
Hemp Composite	HS (Hemp stem)	18.4	0.648	486	0.75
	HB (Hemp bast fibre)	37.7	1.32	2145	1.62

Table 21 - Classification of laminate configurations. The number in brackets refers to the outer ply thickness.

Laminate code	Inner ply material	Outer ply material
A	a	a
B	b	b
A+C	a	c
A+HS	a	HS
A+HB	a	HB
A+HS(3.5mm)	a	HS (3.5mm outer ply thickness)
A+HB(1mm)	a	HB (1mm outer ply thickness)

5.2 Constant Bending Stiffness Laminate Analysis

5.2.1 Scaffold Planks

For scaffold planks, the analysis is performed for a discrete number of 2.6mm thickness plies. For each configuration the number of plies required to meet the minimum deflection criteria in AS1577 (Section 2.8.1.4 of this report) is iteratively determined. The ANSYS model used for calculations in modelled on a standard 1800x230mm scaffold plank from the CarterHoltHarvey hyPLANK range. Commercially this has a thickness of 42mm [58]. A 2.5kN working load limit will be imposed for a heavy duty plank as in Table 7. The static structural ANSYS model used for analysis is shown in Figure 28 using the minimum overhang distance of 150mm at the supports which are modelled simply as line supports. The laminate modulus is calculated using Equation (8).

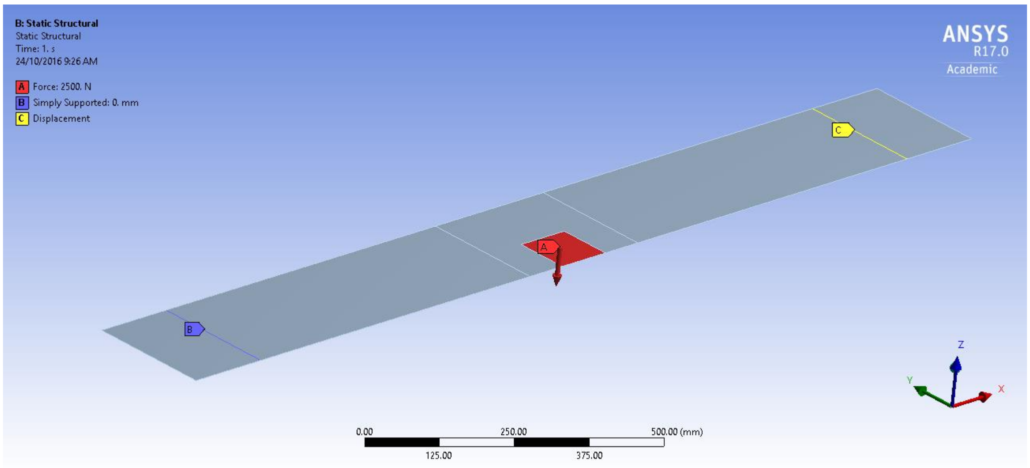


Figure 28 - ANSYS static structural model of scaffold plank bending test

Table 22 details physical properties of the different configurations and

Table 23 details their mechanical properties, including their stress grade. This confirms that a thinner scaffold plank must have a higher stress grade to meet the same bending requirements as a thicker plank of a lower stress grade. Figure 29 (c) plots this trend from data point of each laminate configuration showing a clear downward trend. Because each data point is calculated based on a discrete ply thickness of 2.6mm, the different configurations do not have exactly constant bending stiffness which adds a small error to each point. If analysis was performed for a continuous ply thickness the data points would be expected to lie exactly on the curve.

Table 22 - Physical properties of scaffold plank configurations

Laminate code	No. of plies	Total thickness (mm)	AUD/m^3	AUD/m	kg/m
A	18	46.8	351.56	3.78	4.57
B	16	41.6	401.79	3.84	4.31
A+C	15	39.0	407.75	3.66	4.37
A+HS	16	41.6	368.36	3.52	4.54
A+HB	13	33.8	627.42	4.88	4.54
A+HS(3.5mm)	14	38.2	376.2	3.31	4.27
A+HB(1mm)	16	38.4	444.95	3.93	4.38

Table 23 - Mechanical properties of scaffold plank configurations

Laminate code	CLT E_f (GPa)	Calculated modulus E (GPa)	Specific modulus E/ρ	Maximum principal stress at WLL (MPa)	Stress Grade
A	7.43	9.28	20.61	14.05	F8
B	9.28	11.65	25.89	18.16	F11
A+C	11.31	14.09	28.95	33.83	F17
A+HS	10.69	13.06	27.50	29.34	F14
A+HB	18.29	22.62	38.72	51.58	F34
A+HS(3.5mm)	12.14	14.91	31.17	30.74	F17
A+HB(1mm)	11.71	14.98	26.79	62.42	F17

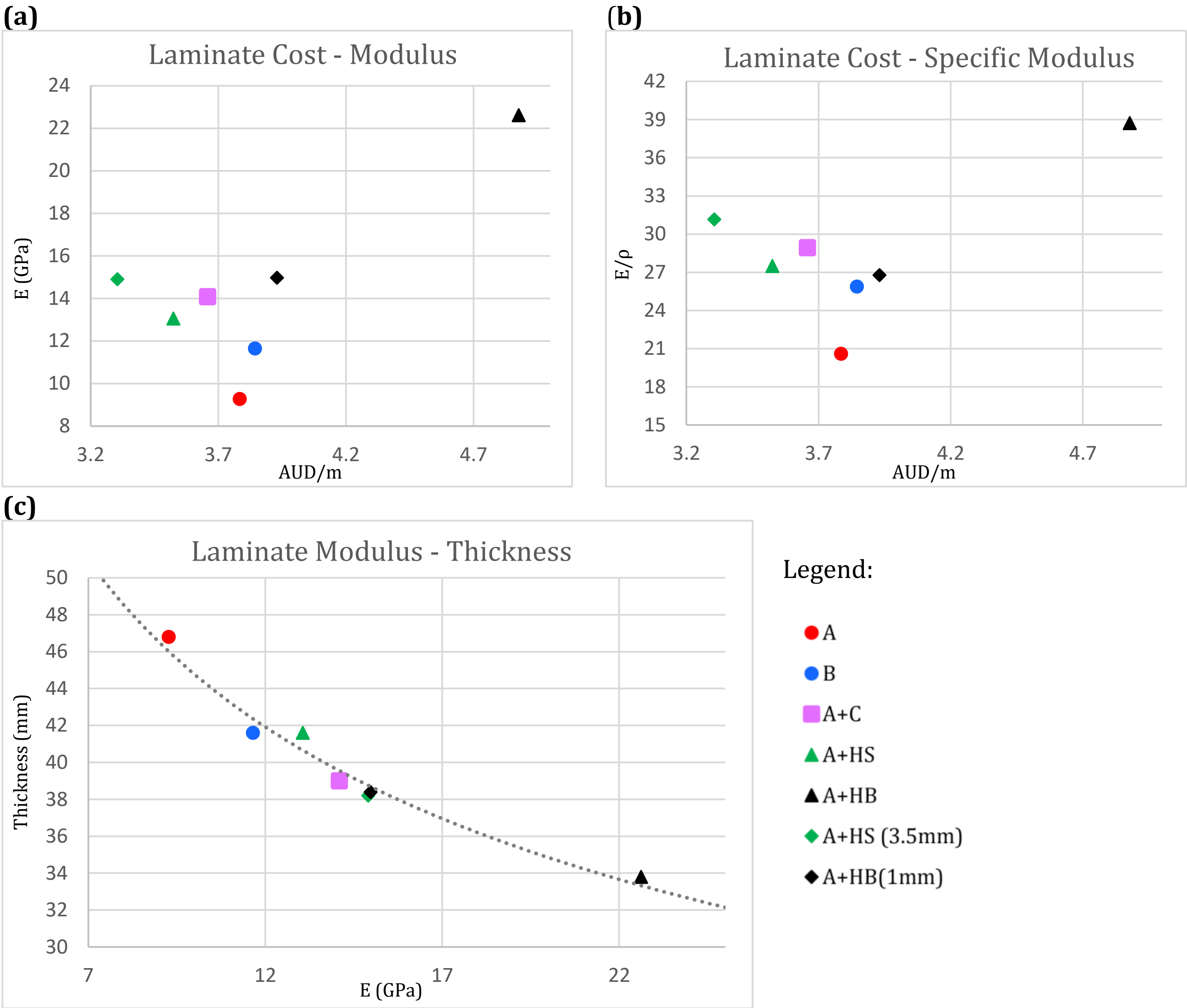


Figure 29 - Cost-performance comparison of scaffold plank configurations for the same bending stiffness. (a) Laminate cost vs modulus. (b) Laminate cost vs specific modulus. (c) Laminate modulus vs thickness confirms the higher modulus required for a thinner scaffold plank.

Figure 29 (a) shows that adding hemp stem composite at the outer plies is able to reduce the scaffold plank cost per metre compared with all-timber laminates, including with the addition of stiffer hardwood at the outer plies. The hemp bast composite is not able to reduce costs and is the most expensive solution based on its estimated cost of 2145 AUD/m^3. The use of hemp stem composite plies is also advantageous in terms of weight. This is shown in Figure 29 (b) where the A+HS(3.5mm) configuration offers a higher specific modulus than the all-timber laminate configurations.

5.2.2 Structural Plywood Flooring

Different plywood configurations will be compared based on their modulus E and second moment of area I for a specific loading scenario. The loading is assumed to be for robust commercial applications with imposed distributed and point loads of 5kPa and 4.5kN respectively as in Table 6. The maximum allowable deflection is span/300 which is calculated simply through a bending deflection equation. The panel is likely to be nailed between joists and cannot be analysed as simply supported, but somewhere between simply supported and fixed. Therefore the bending deflection formula is averaged between these two boundary condition cases will be calculated using Equation (12) which is consistent with example calculations from the Engineered Wood Products Association of Australasia (EWPAA) [43]. This is based only on the concentration load of 4.5kN as this is almost always the limiting load due to the good load re-distribution capabilities of the cross-laminated construction of plywood.

$$\delta_{max} = \frac{PL^3}{104\,EI} \tag{12}$$

Assuming a minimal load distribution width of 400mm, the required stiffness of the panel EI is calculated as 5192.3 x10^3 Nmm^2 per mm width.

The static structural ANSYS model is shown in Figure 30Figure 28, based on plywood test specifications in AS2269.2, shown in Figure 8 with a width of 300mm and length dependent on the laminate thickness. The laminate modulus is calculated using Equation (11).

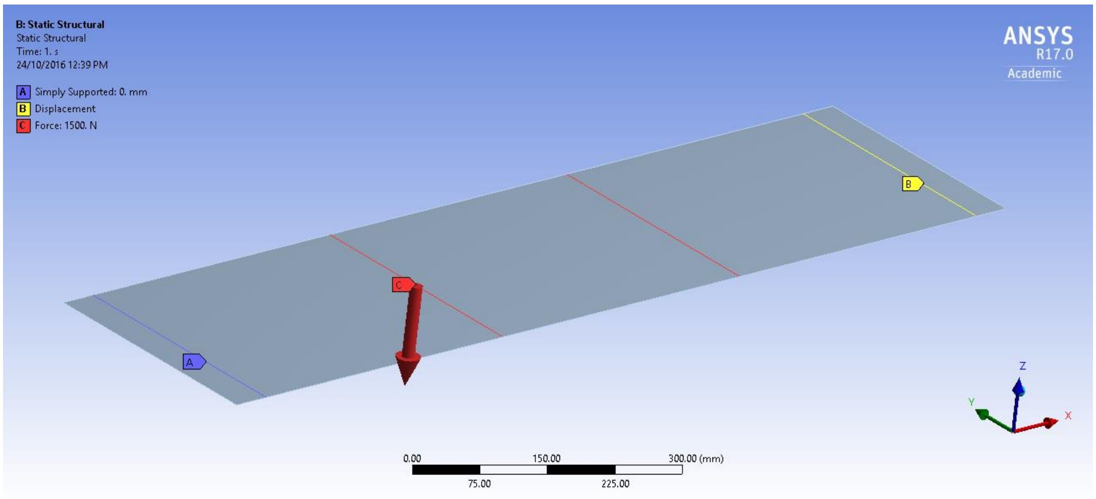


Figure 30 - ANSYS static structural model of plywood bending test

For simplicity, especially in calculating the second moment of area I_{par} of each plywood configuration, the analysis was performed for laminates with all plies of equal thickness. To maintain consistency with the validated FE model using gluelines, the glueline thickness was scaled to maintain the same ply/glue ratio when performing analysis on plies of different thickness. Figure 31 shows an example layup plot, stress plot and polar plot of a 9-ply plywood laminate under 4-pint bending where the plies alternate between 0° and 90°.

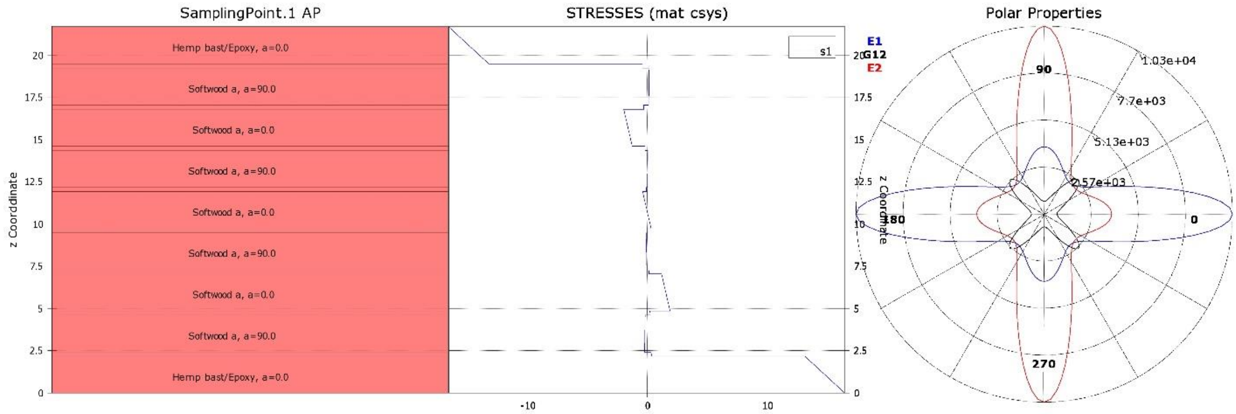


Figure 31 - Layup plot, stress plot and polar plot of 9-ply plywood laminate under 4-point bending

Analysis was first performed using the FE model for plywood with different ply numbers and different outer ply materials. The results of this analysis are shown graphically in Figure 32 (a). Figure 32 (b) shows the same plot for only the A+C and A+B configurations. In this plot the two curves converge at high t_{ply} : $t_{laminate}$ (R) ratios where a higher percentage of the laminate thickness is made up of the stiffer outer ply material. Table 24 lists the 2nd order polynomial functions which best represent the relationship between the plywood modulus and the ratio R. These functions were then used for comparison of different plywood configurations. These relations are only valid when all plies are of equal thickness. Adding outer plies with a different thickness to the rest of the laminate will significantly alter the moment of inertia and modulus of the laminate. Also note that for laminates A and B where all plies have the same modulus, the laminate modulus is independent of the ratio R.

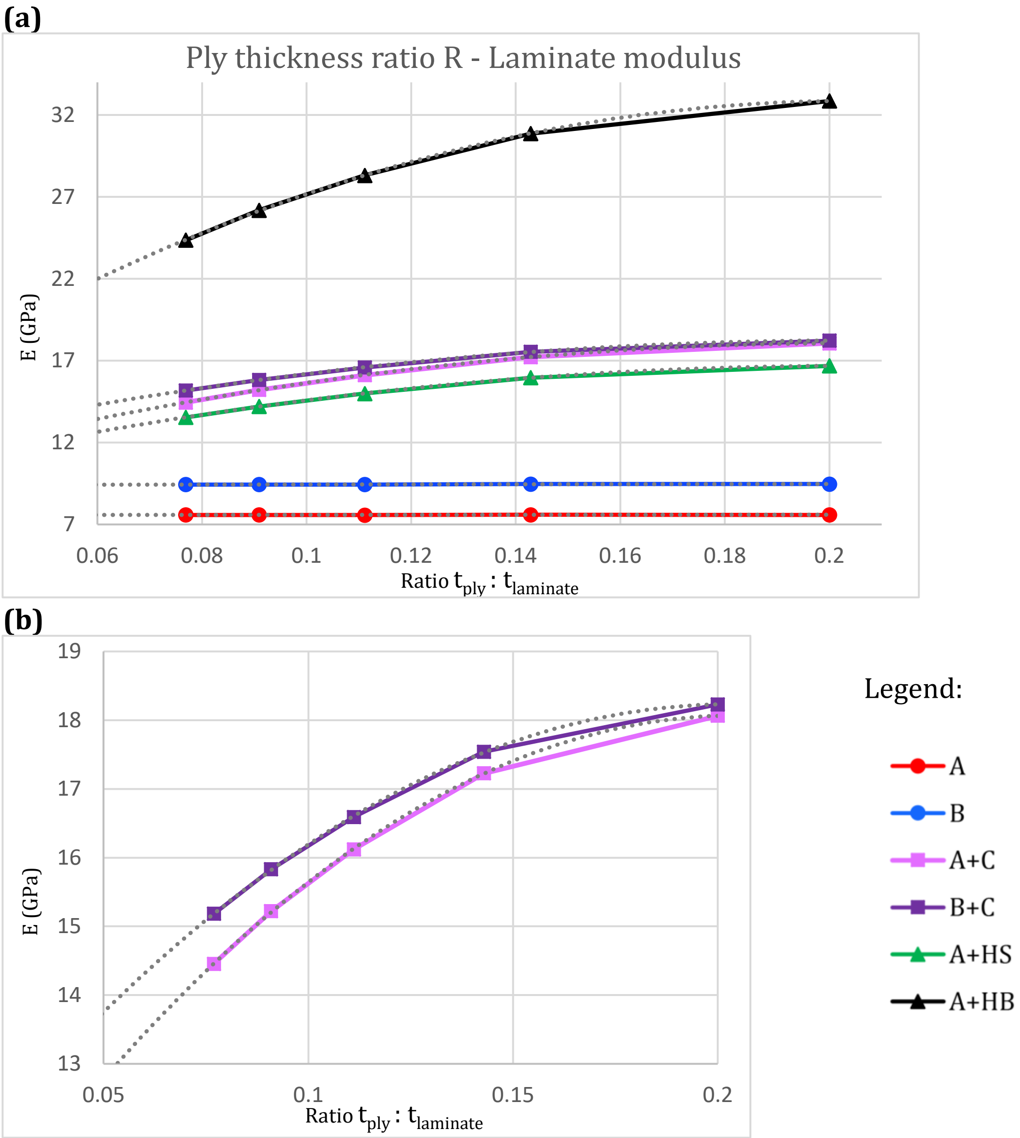


Figure 32 - Relationship between the thickness ratio of plies : total laminate thickness, and the modulus of the laminate. (a) For all laminate configurations. (b) For only A+C and A+B configurations, showing convergence to the outer ply modulus at high ratio values.

Table 24 - Plywood modulus functions dependent on $t_{ply} : t_{laminate}$ ratio R

Laminate code	Plywood Modulus E (Function of Ratio R $t_{ply} : t_{laminate}$)
A	E = 7.584
B	E = 9.448
A+C	$E = -220.85\ R^2 + 90.465\ R + 8.8063$
B+C	$E = -189.97\ R^2 + 77.365\ R + 10.357$
A+HS	$E = -193.26\ R^2 + 79.011\ R + 8.6131$
A+HB	$E = -520.06\ R^2 + 212.8\ R + 11.097$

For simplicity comparison of different configurations was done for only 9-ply laminates with a R ratio of 0.111. Unlike the analysis for scaffold planks, the comparison of plywood comparison is performed for a continuous (instead of discrete) ply thickness which meets the design bending stiffness EI of 5192.3 x10^3 Nmm^2/mm. The required modulus for each configuration is calculated based on this value, and the second moment for each ply thickness. Commercially plies are manufactured at discrete thickness values, however this method allows for a more accurate comparison of costs and performance. In Figure 33 (c), all data points lie exactly on the power curve used to represent the relationship between the laminate thickness and the required modulus for the same bending stiffness. This can be compared to Figure 29 (c) for scaffold planks where the data points do not perfectly fit the curve due to the use of discrete ply thickness'.

Table 25 details physical properties of the different configurations and Table 26 details their mechanical properties, including stress grades. This data is plotted in Figure 33 (a) and (b), comparing the different configurations using the same Ashby-like graphs as in the comparison of different scaffold planks. Again adding the hemp stem composite at the outer plies is seen to be the cheapest option and the hemp bast composite far more expensive than any other configuration. Adding the hemp stem composite plies also offers a reduced cost compared with an all-softwood timber construction. However, it must be emphasised that this comparison is only for plies of equal thickness. The use of different ply outer ply thickness' for the hemp composite material could offer further improved performance as is apparent in the scaffold plank analysis.

Table 25 - Physical properties of structural plywood configurations

Laminate code	No. of plies	Total thickness (mm)	AUD/m^3	AUD/m	kg/m
A	9	23.1	351.56	1.87	2.39
B	9	21.5	401.79	1.98	2.22
A+C	9	18.3	445.21	1.88	2.15
B+C	9	18.1	484.27	2.01	2.12
A+HS	9	18.7	381.43	1.64	2.13
A+HB	9	15.3	750.02	2.64	2.26

Table 26 - Mechanical properties of structural plywood configurations

Laminate code	Calculated modulus E (GPa)	Specific modulus E/ρ	Stress Grade
A	7.58	16.85	F5
B	9.45	21.00	F8
A+C	15.21	29.75	F17
B+C	15.82	30.95	F17
A+HS	14.20	28.74	F17
A+HB	26.14	40.62	F34

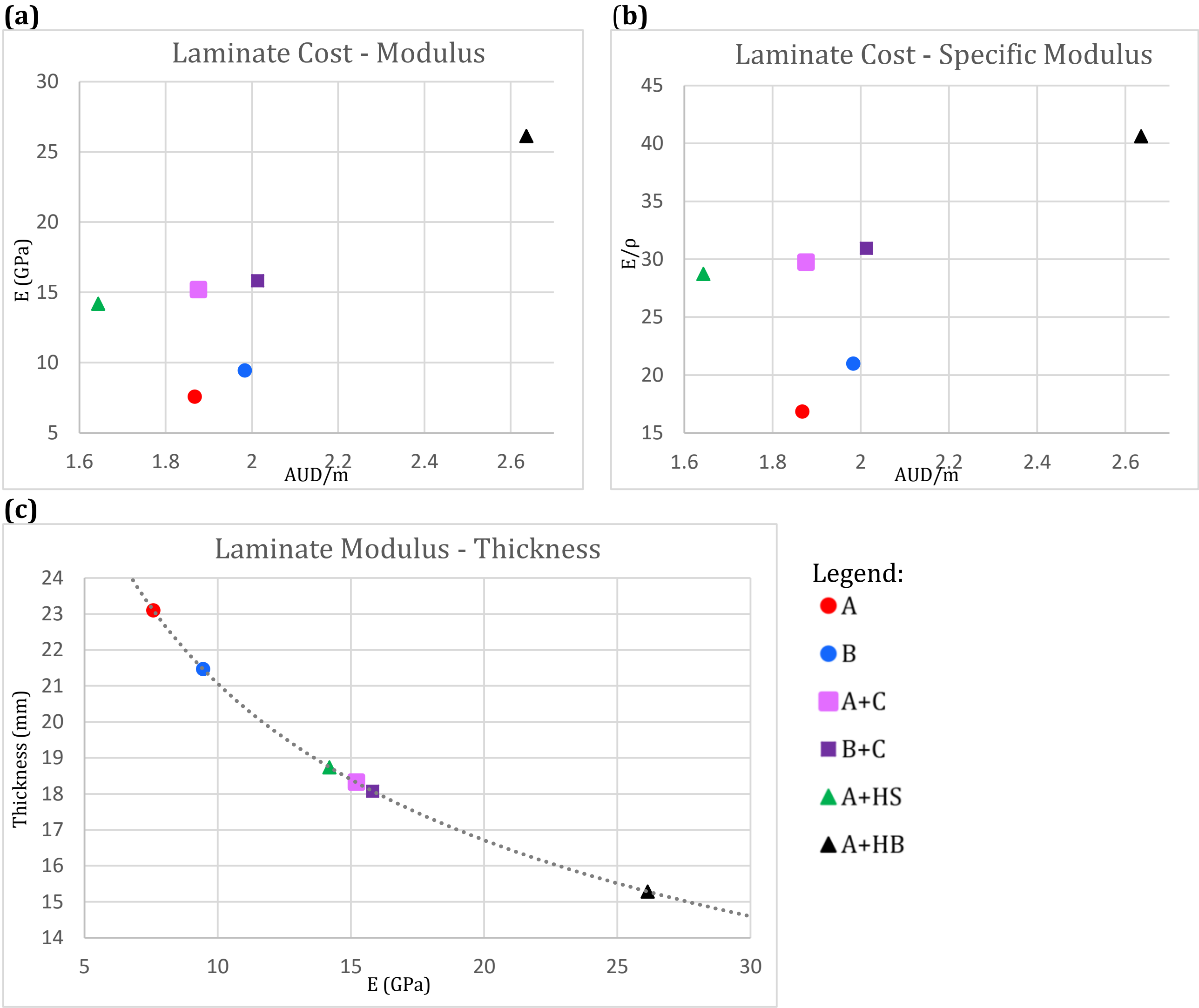


Figure 33 - Cost-performance comparison of structural plywood configurations for the same bending stiffness. (a) Laminate cost vs modulus. (b) Laminate cost vs specific modulus. (c) Laminate modulus vs thickness confirms the higher modulus required for a thinner plywood sheet.

5.3 Constant Thickness Laminate Analysis

Constant or near-constant thickness laminate analysis is performed in order to directly assess the potential stiffening capabilities of the hemp composite materials at the outer plies of timber laminates and to set benchmark figures for the maximum hemp composite cost in order for it to be commercially feasible for stiffening laminated timber products. Typically, timber laminates are composed of all single-species timber of a similar modulus. Therefore, the replacement of hemp composite material at the outer plies of standard 10GPa timber layups is compared to equivalent laminates composed of all-timber plies with a higher modulus. Scaffold planks and structural plywood examples are used for this comparison, however the results can be equally extended to various laminated timber applications.

5.3.1 Scaffold Planks

The modulus and stress grade of different laminates including hemp composites are compared to a standard F11 construction with 2.6mm plies in Table 27. The same FE model analysis technique from Section 5.2.1 is again used for this comparison. Table 28 then shows the modulus required for an equivalent all-timber construction where are plies have the same modulus. Because detailed timber costs are not known, a linear approximation has been used from the timber cost data in Table 20.

Table 27 - Modulus of different scaffold plank ply configurations for near-constant thickness

Laminate code	Total Thickness (mm)	Calculated modulus E (GPa)	Stress Grade
B	41.6	11.65	F11
B+HS(2.6mm)	41.6	14.74	F17
B+HB(2.6mm)	41.6	21.71	F34
B+HS(3.5mm)	43.4	15.63	F17
B+HB(1mm)	38.4	17.06	F22

Table 28 - Cost comparison of using hemp composite at outer plies to all-timber plywood laminate with equivalent modulus

Laminate code	Laminate modulus	Required timber modulus for equivalent all-timber laminate (GPa)	Estimated timber ply cost (AUD/m^3)	Max cost of outer composite plies for break-even (AUD/m^3)	Profit margin (AUD/m^3)
B+HS(2.6mm)	14.74	13	511	1278	792
B+HB(2.6mm)	21.71	21	782	3445	1301
B+HS(3.5mm)	15.63	14	545	1151	665
B+HB(1mm)	17.06	16	613	5436	3291

This comparison shows that adding the hemp bast composite at the outer plies can almost double the laminate modulus and adding only a 1mm layer similar to what was produced can increase the modulus by 46%. Compared to estimated timber costs for equivalent all-timber layups, a large cost margin exists for the addition of stiffer outer plies to a lower modulus layup. This reinforces the hypothesis that adding a different outer ply material is the most cost effective method of improving laminate stiffness. This is especially noticeable for a scaffold plank which generally requires a high thickness, therefore increasing the contribution of the stiff outer plies to the total bending stiffness. The calculated profit margin is based on the estimated composite material costs from Table 20. This suggests that using the more expensive hemp bast composite is more cost effective if a higher laminate modulus is desired. This differs from results for constant bending stiffness where the cheaper hemp stem composite has the greatest impact on cost reduction. In all cases, a large estimated profit margin exists, providing room for realistic manufacturing costs.

5.3.2 Structural Plywood

For plywood, the different laminate configurations are compared to a 9-ply layup of 2.4mm timber plies with a 10GPa modulus in Table 29. The same FE model analysis technique from Section 5.2.2 is again used for this comparison. Table 30 then shows the modulus required for an equivalent all-timber construction where are plies have the same modulus, similar to the scaffold plank comparison. Note that no timber ply costs is given for a 32GPa modulus as this is above known moduli of timber species.

Table 29 - Modulus of different plywood ply configurations for near-constant thickness

Laminate code	Total Thickness (mm)	Calculated modulus E (GPa)	Stress Grade
B	21.6	9.44	F8
B+HS(2.4mm)	21.6	15.45	F17
B+HB(2.4mm)	21.6	28.94	F34
B+HS(3.5mm)	23.8	18.55	F27
B+HB(1mm)	18.8	18.93	F27

Table 30 - Cost comparison of using hemp composite at outer plies to all-timber scaffold plank with equivalent modulus

Laminate code	Laminate modulus	Required timber modulus for equivalent all-timber laminate (GPa)	Estimated timber ply cost (AUD/m^3)	Max cost of outer composite plies for break-even (AUD/m^3)	Profit margin (AUD/m^3)
B+HS(2.4mm)	15.45	17	647	1524	1038
B+HB(2.4mm)	28.94	32	-	-	-
B+HS(3.5mm)	18.55	20	748	1359	873
B+HB(1mm)	18.93	20.5	765	4939	2794

This comparison shows that adding hemp composite outer plies to a plywood layup produces an even more pronounced increase in modulus than for scaffold planks, more than doubling the plywood modulus by adding 1mm hemp bast composite plies. This is because plywood has an alternating 0° and 90° layup so adding a stiffer material in one direction has a greater impact overall. Again, the exists a considerable cost margin for the addition of hemp composite plies. Despite this, there is smaller design cost space than for scaffold planks which is likely a result of the lower thickness of the plywood layups reducing the impact of the outer ply modulus on the laminate bending stiffness.

6 Small-Scale Hemp Composite/Timber Laminate Product Demonstration

In order to demonstrate the use of hemp composite material at the outer plies of a timber laminate, additional composite sheets were produced and laminated with radiata pine timber veneers of approximately 10GPA modulus. A LVL laminate using the hemp stem/epoxy composite is shown in Figure 34, and with the thinner hemp bast/epoxy composite in Figure 35. The laminates were made using the same technique as in Section 4.1 for timber LVL specimens, but with a quicker setting PURBOND HB S109 polyurethane adhesive. This has an assembly and press time of 10 minutes and 25 minutes respectively. This was appropriate due to the much smaller size of the plies which could be glued more quickly. The same pressing pressure of 1MPa was used. The laminates were then cut using a waterjet cutter, allowing inspection of the laminate cross-section.

The hemp stem sheets are seen to have a highly uneven outer surface, though bonding to the timber veneers is completely flat. This suggests that the hemp sheet may be better suited to use within the laminate instead of only at outer plies.

(a)
(b)


Figure 34 - Small-scale timber laminate with hemp stem composite at outer plies. (a) Full view. (b) End-section view.

The hemp bast sheet is inherently much flatter and offers a much more uniform surface. The green, bamboo-like and glossy appearance also evokes the possibility of its use for applications requiring an aesthetic finish including flooring and decorative wall panels. Unlike the stem segments, the hemp bast fibres are able to be easily shaped and moulded. This opens up opportunities for use in curved mouldings to be made for specific applications.

(a)

(b)

Figure 35 - Small-scale timber laminate with hemp bast composite at outer plies. (a) Full view. (b) Side-section view.

The main question regarding the performance of these laminates in bending is the effectiveness of bonding between the timber and composite plies. These laminates serve as a demonstration of possible laminated timber products. Their performance has not been tested in bending, however the effects of poor bonding, including debonding and slippage, should only become significant at large curvatures. The non-uniform surface of the hemp stem composite was of primary concern for bonding with timber, however the laminate in Figure 34 shows the contacting surface to be flat.

The polyurethane adhesive used is moisture cured and requires the veneers to have at least 8% moisture, but preferably 10-12%. The composite surface which is composed of small sections of hemp fibre, but largely resin, giving it a highly smooth surface finish. This likely does not have the moisture content or surface roughness required for a strong bond to be formed. An epoxy adhesive would bond very strongly to the composite surface, however its bond with the timber surface would be much weaker. The composite/timber interface demands an adhesive that is able to bond well to both surfaces and this is an essential requirement for the integration of natural fibre composites into timber laminates.

7 Conclusions and Recommendations for future work

The primary aim of this thesis was to develop a low cost natural fibre composite sheet material able to strengthen and stiffen timber laminates, potentially allowing the use of low grade timber for the remaining plies. Industrial hemp stems were used as a readily available natural material with high stiffness and strength. Two minimal-processing methods for unidirectional (UD) fibre hemp composite manufacturing were established. Firstly, by splitting the as-received stems longitudinally and crushing, the stem segments could be laid and pressed with polymer resin to produce a flat composite sheet. This is estimated to have a material cost of 422-550AUD/m^3. Alternately, only the outer bast fibres can be used, which contribute chiefly to the stiffness of the hemp stems. The bast fibres are readily stripped from the woody stem after crushing and can similarly be pressed with resin to a thin composite sheet. Using this process has an estimated material cost of 1772-2517AUD/m^3. The relatively low cost compared to traditional NFRP composites is achieved by skipping major processing steps used for natural fibres including decortication, spinning into yarn or tows, and washing or chemical treatments. This is able to be avoided by preserving the natural alignment of fibres in the plant stem.

Tensile testing proved the concept of a minimal-processing natural fibre composite sheet material with good mechanical properties. The hemp stem sheet had an average tensile modulus and strength of 18.4GPa and 69.8MPa respectively, while the hemp bast fibre sheet performed much better with a modulus and strength of 37.7GPa and 145MPa respectively. The 37.7GPa modulus far surpasses reported values for other unidirectional natural fibre composites in literature, however the strength is significantly lower. This draws attention to the major difficulties associated with using natural fibres. The inherent non-uniformity of the fibres is even more substantial for unprocessed fibres, leading to stress concentration around defects. This is a major cause of failure in the hemp composites and is an important source of the high variability of the strength and modulus of NFRP composites. Comparison of the hemp composite's mechanical properties to the standard stress grading system for plywood and other laminated timber products highlighted the potential implications for stiffening and strengthening of timber laminates. Both strength and stiffness of the composite materials corresponded with stress grades much higher than the approximately 10GPa modulus softwood timber species typically used for laminated timber constructions.

The potential stiffening capability of using the hemp composite at the outer plies of timber laminates was assessed using validated FE models of scaffold planks and structural plywood. Overall, comparing the results of the of the constant thickness laminate analysis to the constant bending stiffness analysis shows that the differing hemp stem and hemp bast composites are better suited to different applications based on the desired outcome. The hemp stem composite is more cost effective when used to reduce the number of timber plies required to achieve the same bending stiffness as an all-timber laminate consisting of the same lower grade plies. This is due to its significantly lower density and lower cost compared with comparable timber species. The hemp bast composite is more cost effective when used purely to produce laminates with a higher modulus. Importantly, it must be noted that all cost analysis is based on estimated timber and composite costs, however the very high cost margins calculated in the constant thickness analysis strongly indicate that the use of the hemp composite material is commercially feasible. The successful implementation of similar products could boost the profitability of Queensland and Australia's timber industry, allowing for cheaper or downgraded timber to be used in high stiffness laminates.

Small-scale product demonstration models were produced with hemp composite sheets at the outer plies. Inspection of these laminates revealed the more far-reaching potential applications of the manufacturing techniques, both structurally and non-structurally, including skateboards and decorative panels. The ability of the bast fibres to be shaped and moulded evens further broadens the potential commercial applications of the material.

There is very little published mechanical property data for NFRP composites, especially unidirectional composites, and even less for fibres that are not processed into a yarn or other form. This may largely be due to the high variance and lack of repeatability of natural fibre properties, limiting their commercial use. The limited amount of published data underlines the strong potential for publication of the strength and stiffness results for the hemp composite, especially due to the non-traditional processing methods used. Some journals which were of interest when researching the topic and may benefit from this development in the manufacturing of natural fibre composite materials include the Journal of Composite Materials, Composites Science and Technology, Composites Part A: Applied Science and Manufacturing, Materials Today, and Polymer-Plastics Technology and Engineering. The International Conference on Composite Materials (ICCM) is a conference aimed at the promoting research and development into composite structures and may also be an avenue for publication. This project has progressed in conjunction with the Queensland Government Department of Agriculture and Fisheries, Salisbury Research Facility and is not expected for publication prior to a review of the conclusions of this thesis.

In this project, hemp fibres were exclusively used for the development of natural fibre composite sheets as hemp stalks were most readily available. For future work, other high modulus natural fibres including flax and jute could be used similarly to assess their ease of manufacturing and composite properties. Further recommendations for future work are listed as follows:

- Investigation into the required pressing pressure, pressing time and number of pressing cycles required to produce crushed stems suitable for preparing composite sheets.
- Investigation and quantitative analysis of the entrapment of air during pressing of the composites leading to porosity in the matrix and methods for reducing porosity.
- Washing or chemical treatment of the as-received or crushed stems in order to remove foreign materials including dirt and improve bonding between the matrix and fibres.
- Selection of an optimal polymer matrix material for low cost and high composite performance.
- Development and selection of a suitable adhesive able to form a strong bond between both timber and the hemp composite surface composed of hemp fibres and polymer matrix.
- Finally, much more testing is required to produce a large and reliable dataset of mechanical and physical properties of the hemp composites. Flexural testing of the composite/timber laminates is also needed to ensure the transfer of stress to the outer composite plies and subsequent stiffening of the laminate.

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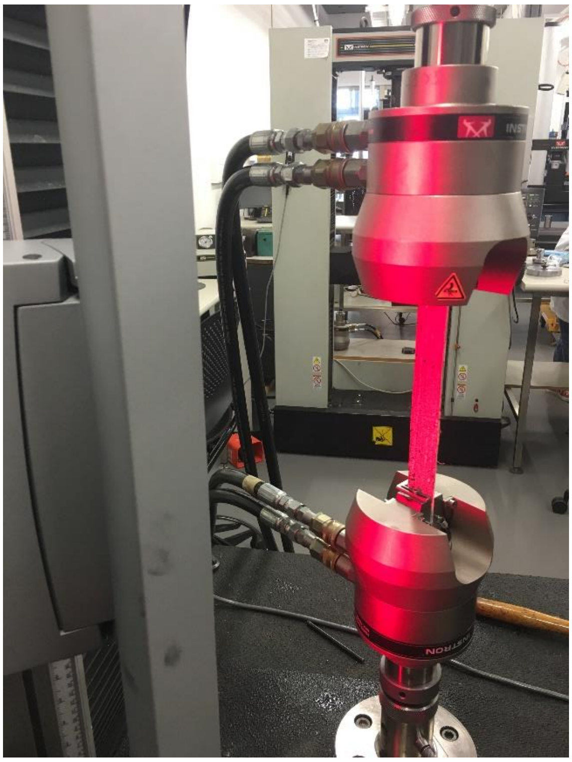
Appendix

Appendix A.   Hemp composite tensile testing procedures

The following image shows a test specimen in tensile testing with DIC.



Appendix B. Hemp bast/polyurethane composite sheet

The hemp bast/polyurethane composite sheet sample is shown after removal from the press and after cutting into test specimens.

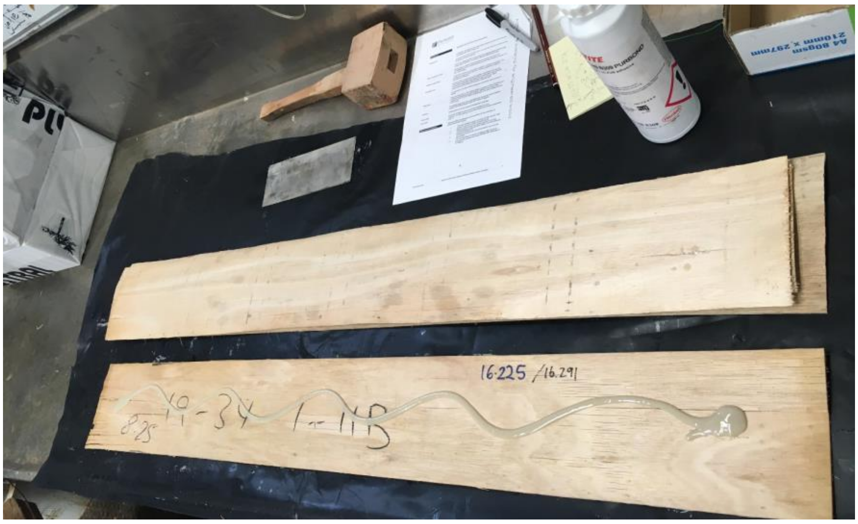
Appendix C. LVL sample preparation procedures

Appendix C.1 Non-destructive testing of timber veneers

Apparatus for measuring elastic modulus of timber veneers using non-destructive testing.

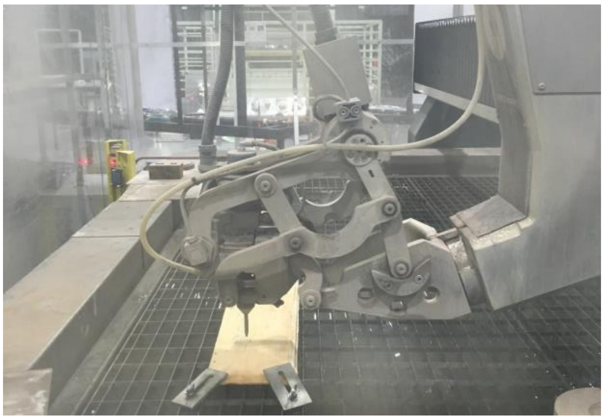
Appendix C.2 Gluing and pressing timber veneers

Spreading a measured quantity of polyurethane between each ply and pressing in a Shimadzu Universal Testing Machine with spindle at 0.5mm/min up to maximum pressure of 1MPa.



Appendix C.3 Waterjet cutting of LVL specimens

After waterjet cutting, specimens were hammered and/sawn out of larger plank and lightly sanded.



Appendix D. Ply properties for ANSYS modelling

8GPa modulus Timber a:

Properties of Outline Row 5: Softwood a

	A	B	C
1	Property	Value	Unit
2	Density	450	kg m^-3
3	Orthotropic Elasticity		
4	Young's Modulus X direction	8000	MPa
5	Young's Modulus Y direction	266.7	MPa
6	Young's Modulus Z direction	266.7	MPa
7	Poisson's Ratio XY	0.35	
8	Poisson's Ratio YZ	0.35	
9	Poisson's Ratio XZ	0.35	
10	Shear Modulus XY	400	MPa
11	Shear Modulus YZ	100	MPa
12	Shear Modulus XZ	400	MPa
13	Ply Type		
14	Type	Regular	

10GPa modulus Timber b:

Properties of Outline Row 6: Softwood b

	A	B	C
1	Property	Value	Unit
2	Density	450	kg m^-3
3	Orthotropic Elasticity		
4	Young's Modulus X direction	10000	MPa
5	Young's Modulus Y direction	333.3	MPa
6	Young's Modulus Z direction	333.3	MPa
7	Poisson's Ratio XY	0.35	
8	Poisson's Ratio YZ	0.35	
9	Poisson's Ratio XZ	0.35	
10	Shear Modulus XY	500	MPa
11	Shear Modulus YZ	125	MPa
12	Shear Modulus XZ	500	MPa
13	Ply Type		
14	Type	Regular	

20GPa modulus Timber c

Properties of Outline Row 4: Hardwood c

	A	B	C
1	Property	Value	Unit
2	Density	725	kg m^-3
3	Orthotropic Elasticity		
4	Young's Modulus X direction	20000	MPa
5	Young's Modulus Y direction	666.7	MPa
6	Young's Modulus Z direction	666.7	MPa
7	Poisson's Ratio XY	0.35	
8	Poisson's Ratio YZ	0.35	
9	Poisson's Ratio XZ	0.35	
10	Shear Modulus XY	1000	MPa
11	Shear Modulus YZ	250	MPa
12	Shear Modulus XZ	1000	MPa
13	Ply Type		
14	Type	Regular	

1GPa modulus adhesive glue:

	A	B	C
1	Property	Value	Unit
2	Density	1.2E-09	mm^-3 t
3	Isotropic Elasticity		
4	Derive from	Young's M...	
5	Young's Modulus	1000	MPa
6	Poisson's Ratio	0.316	
7	Bulk Modulus	9.058E+08	Pa
8	Shear Modulus	379.94	MPa
9	Ply Type		
10	Type	Isotropic	

18.4GPa modulus Hemp stem/Epoxy composite:

	A	B	C
1	Property	Value	Unit
2	Density	450	kg m^-3
3	Orthotropic Elasticity		
4	Young's Modulus X direction	18400	MPa
5	Young's Modulus Y direction	613.33	MPa
6	Young's Modulus Z direction	613.33	MPa
7	Poisson's Ratio XY	0.35	
8	Poisson's Ratio YZ	0.35	
9	Poisson's Ratio XZ	0.35	
10	Shear Modulus XY	920	MPa
11	Shear Modulus YZ	230	MPa
12	Shear Modulus XZ	920	MPa
13	Ply Type		
14	Type	Regular	

37.7GPa modulus Hemp bast/Epoxy composite:

	A	B	C
1	Property	Value	Unit
2	Density	450	kg m^-3
3	Orthotropic Elasticity		
4	Young's Modulus X direction	37700	MPa
5	Young's Modulus Y direction	1256.7	MPa
6	Young's Modulus Z direction	1256.7	MPa
7	Poisson's Ratio XY	0.35	
8	Poisson's Ratio YZ	0.35	
9	Poisson's Ratio XZ	0.35	
10	Shear Modulus XY	1885	MPa
11	Shear Modulus YZ	471.25	MPa
12	Shear Modulus XZ	1885	MPa
13	Ply Type		
14	Type	Regular	